(IN)ATTENTION FOR CREATIVITY

MARIJE STOLTE

Unraveling the neural and cognitive aspects of (mathematical) creativity in children

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(In)attention for creativity

Unraveling the neural and cognitive aspects of (mathematical) creativity in children

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Voor mijn ouders

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General introduction

Scope

Although creativity is valued, the idea of bridging creative thinking with mathematics, a domain with a large focus on convergent thinking and standardized tests, is often not put into practice in the classroom. Because the topic of mathematical creativity in children has not received the attention it deserves, a discrepancy has developed between the value of creative thinking held by society on the one hand and the emphasis on focused attention and convergent thinking in schools on the other hand. A better understanding about the role of creativity in mathematics and its underlying cognitive functions, especially in children who are rapidly developing their worldview and their cognitive skills, could greatly benefit society. By incorporating the cognitive functions and attentional processes that are important for both creative thinking and mathematics in developmental frameworks, fostering creativity during primary school can be implemented, culminating in a more well-rounded education. However, while creative and divergent thinking are increasingly appreciated, the underlying neural and cognitive functions are still ill-understood. The aim of this thesis, therefore, is to shed a light on what underlying cognitive and neural abilities are conducive to creativity in primary school children, particularly in the domain of mathematics. As depicted in Figure 1, each chapter of this dissertation describes the findings on one of these topics and together form a comprehensive picture of the underlying factors of creativity as a whole and in the domain of mathematics.

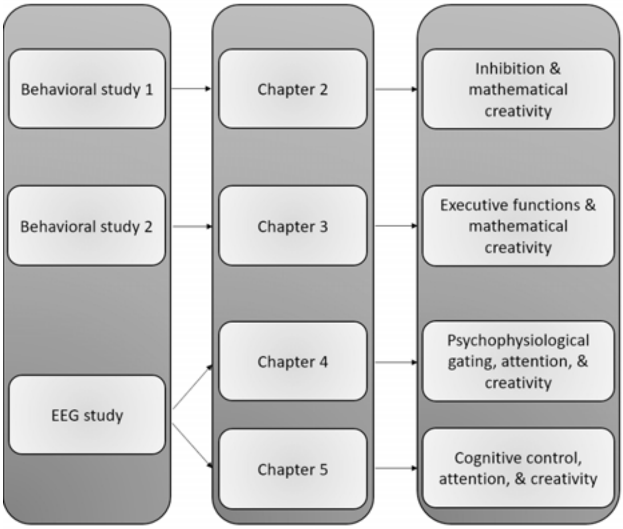

Figure 1. An overview of the main topics as structured in this dissertation.

Theoretical background

Due to the evolution of the prefrontal cortex and the resulting higher cognitive functions, humans and other mammals are capable of having conscious thoughts (Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006; Fuster, 2001; Ruff, Trinkaus, & Holliday, 1997). These higher cognitive functions are indispensable for our daily activities (Garon, Bryson, & Smith, 2008) and are commonly named executive functions. Although there is still much debate about the subcomponents of executive functioning (for review, see Jurado & Rosselli, 2007) combined, the executive functions are responsible for top-down control and represent the higher-order cognitive functions that are called upon during goal-directed behavior (Karr et al., 2018; Miyake et al., 2000). For instance, we make an appeal to executive functions when we follow a recipe or when we try to complete a mathematical assignment that requires using different strategies over the course of several steps. Furthermore, executive functions also play a role in composing our behavior when we are angry or sad or when we notice we have made a mistake while trying to follow the recipe. In this case it is important to respond swiftly and flexibly to rectify the mistake and still bring a decent cake to the table.

Apart from executive functions, another feature that is essential in our fast-paced society is the ability to be creative and create things that are valuable in a given setting (Bell, 2010). During the eighteenth century, the foundation of modern-day creativity was laid by removing genius and supernatural abilities from the description of creativity and instead describing creativity as something that everybody can develop albeit with changing potential (McWilliam, 2009).

The thinking process and behavior of creative people are commonly associated with high distractibility and atypical attention (for a review, see Hoogman, Stolte, Baas, & Kroesbergen, 2020). In fact, often, highly creative children are diagnosed with an attentional disorder such as Attention Deficit/Hyperactivity Disorder (ADHD) because of their high distractibility and reduced inhibition (Carson, Peterson, & Higgins, 2003; Gonzalez-Carpio, Serrano, & Nieto, 2017). Despite the disadvantages of distractibility, creative behavior seems to thrive on it (Carson et al., 2003). However, which type of reduced inhibition or at what point in the attentional process dispersed attention might be beneficial to creativity is still unknown.

In contrast to the relatively slow natural evolution of the prefrontal cortex, which brought about executive functions, the cultural evolution occurs at a much faster rate. Consequently, potential problems of the future are unknown or novel to us, and creativity is required to solve them (Plucker, Beghetto, & Dow, 2004; Sternberg, Lubart, Kaufman, & Pretz, 2005). Creativity, attentional processes, and executive functions connect here and make it possible to successfully navigate our way through various situations. In addition to creativity, many problems that we face during everyday life involve mathematics. Therefore, it is extremely important that mathematical creativity is promoted during education, as it is required across society (UNESCO, 2012). Although many people see mathematics as a static discipline with fixed rules and outcomes and thus no room for creativity, in reality the opposite is true (Borwein, Liljedahl, & Zhai, 2014; Sriraman, 2004). Mathematical creativity, however, is often valued but not taught in the current classroom situation, where convergent assignments are still the norm (Bolden, Harries, & Newton, 2010; Kattou, Kontoyianni, Pitta-Pantazi, & Christou, 2013; Kwon, Park, & Park, 2006; Mann, 2005; Plucker et al., 2004; Thijs, Fisser, & Van der Hoeven, 2014).

The research that is described in this dissertation lies on the intersect of these previously mentioned concepts. Given the hypothesized positive and negative aspects of reduced inhibition and dispersed attention, we studied to what extent individual differences in executive functions and psychophysiological measures of attention inform our understanding of (mathematical) creativity in children between 8 and 13 years old. To achieve this, we combined behavioral instruments that measure creativity, mathematics, attentional difficulties, and executive functions with electroencephalography (EEG) and electromyography (EMG) paradigms that measure sensorimotor gating, selective attention, and sensory gating. Integrating behavioral and neurocognitive measures provides valuable new insight into the mechanisms that are fundamental for creative cognition, attention, and mathematics. In other words, although much can be gleaned about creativity, attention, and mathematics during childhood from self-report measures and other psychological methods, cognitive and neuroscientific methods provide a more mechanistic account of the underlying processes of these skills, which will greatly increase the explanatory power of this study (Blankenstein, 2019; Van Duijvenvoorde & Crone, 2013).

This general introduction provides a description of creativity, executive functions, selective attention, filtering of incoming stimuli, and mathematics, followed by an outline of the empirical chapters of the thesis.

Creativity

Despite the growing interest in creativity in the scientific community, Kim (2011) reported the alarming result that creativity scores have been declining since the 1990s. This decline was especially visible from kindergarten through 6th grade. Possible explanations for this decline might be found in the amount of time children are currently spending on electronics, such as watching television or playing videogames (Kim, 2011). These activities leave very little to be imagined. Another explanation for this decline is that education does not stimulate or nurture creativity enough and instead may even discourage it because of the large focus on standardized testing and convergent thinking (Krampen, 2012; Mann, 2005; Sternberg, 2007; Vong, Mak, Leung, & Chang, 2020). This decline in creativity and the lack of expertise of educational professionals about fostering this ability generates a demand to understand creativity and its underlying processes better, especially in children who are still developing, because creativity has been identified as one of the most important abilities of the future (Bronson & Merryman, 2010; IBM Institute for Business Value, 2010; Thijs et al., 2014).

Currently, the focus of creativity research and definitions is placed on the influence of social and environmental processes (McWilliam, 2009). Within this view, creativity becomes a skill that can be fostered and taught. As such, this view on creativity emphasizes the importance of promoting creativity in educational programs.. At first, researchers debated whether creativity was domain-general or domain-specific (Baer, 1998; Plucker, 1998). However, a more unified theory has since formed that includes both aspects (Baer & Kaufman, 2005; Willemsen, Schoevers, & Kroesbergen, 2019). An education focused model of creativity is the hybrid model by Plucker and Beghetto (2004). They propose that creativity has both specific and general components and that, within the sociocultural view of creativity (Corazza & Glăveanu, 2020), the amount of specificity and generality will change across different contexts. Educational programs should thus encourage children to be creative in domain-general and domain-specific ways. Therefore, we chose to adopt the following definition of creativity in this dissertation: the ability of an individual to create a tangible or abstract product that can solve a problem, serve a purpose, or can answer a question (Plucker et al., 2004; Runco & Jaeger, 2012). In addition to this definition, we also approached creativity in a way that creative potential can differ between individuals and environments (Barsalou, 2008; Corazza & Glăveanu, 2020).

In line with the sociocultural view of creativity (e.g., Corazza & Glăveanu, 2020; Glaveanu et al., 2020), and according to the perception-action framework, cognitive and creative processes must be viewed as situated and distributed across brain, body, person, and environment (Barsalou, 2008; Stoffregen, 2003; Van Dijk, Kroesbergen, Blom, & Leseman, 2019; Wilson, 2002). As such, the mind does not work on abstract problems: it functions through the connections that it has with the body, which in its turn is connected to and interacts with the outside world. Hence, the foundation of human cognition does not lie in abstractness and centralization but may instead be related to sensorimotor processing and other early attentional processes. For instance, when the environment is very rich, it offers many affordances for the child to use creatively. Following this hypothesis, the development of creativity depends in part on how the child perceives and acts on these affordances to be creative. In addition, this also means an active perception of the environment, in which a diversity of stimuli can be perceived and noticed and reach consciousness without being too overwhelming or overstimulating, which might depend on attentional skills and other processing abilities.

Mathematics

Mathematics is one of the cornerstones of primary education because some rudimentary knowledge of mathematics is necessary to navigate standard everyday activities successfully. For instance, we use mathematics to tell time, measure a room, and to calculate the discount price for a coat we want to buy that is 25% off. Here, a brief overview is given of mathematics education in The Netherlands. To ensure that children develop sufficient mathematical abilities during primary school, the government composed several core objectives to serve as guidelines for curriculum development (Greven & Letschert, 2006). Amongst others, these objectives state that children should learn math language; understand the structure and context of amounts, round numbers, decimals, fractions, percentages, and ratios and how to apply this knowledge in practical situations, such as when they are telling time or during monetary transactions; acquire the ability to estimate; develop strategies to facilitate addition, subtraction, division, and multiplication; become familiar with how to use a calculator; learn how to solve basic geometry problems; and learn how to measure and calculate (e.g., weight, length, temperature, volume) (Noteboom, 2017).

Children first learn the basics of mathematics in kindergarten, such as counting, addition, and subtraction. During these first years the focus is on developing number sense and learning the first mathematical signal words such as before, first, and last. In grade 1 this knowledge is extended by the development of useful strategies with solutions up and including 20 in grade 1 and up to 100 in grade 2. Starting in grade 3, there is a sharp increase in the different topics and learning goals of mathematics education. For instance, children are expected to understand large units and should be able to give meaning to numbers by relating them to everyday life. Grade 3 is also the time in which children learn to use decimal numbers, work with percentages, ratios, and the relativity of numbers. In addition, they start to explore measuring, telling time, estimating, and learn the basics of geometry. Once children reach grade 4, the emphasis is placed on working with fractions, giving meaning to decimal numbers, applying useful strategies to add or subtract, calculating percentages, money, measuring, and learning about geometry. Especially the domains of geometry and measuring are further expanded during grade 5 and 6 in which children learn about the coordinate system, diagrams, symmetry, the connotations of a wind rose, combinations of magnitudes, temperature, and weight (Greven & Letschert, 2006; Noteboom, Aartsen, & Lit, 2017).

Mathematical creativity

What we can distill from these objectives for primary school mathematics is that while creativity is identified as an important aspect (Gravemeijer, 2007), it does not seem to be implemented in practice. At a first glance, the relationship between creativity and mathematics seems farfetched. However, mathematics goes beyond the regular standardized tests and convergent procedures that are generally learned in school. For instance, mathematical creativity is dependent on thinking outside of the general frame of reference in order to solve a problem (Bahar & Maker, 2011; Sak & Maker, 2006), an ability that is very useful for thinking of original solutions. Furthermore, creativity is also imperative when people are faced with a problem for which they do not have a learned or practiced solution, which is often the case in mathematics (Batey & Furnham, 2006). This connection between creativity and mathematics is also present in children. For instance, children can be creative in the domain of mathematics when they think of something for the first time, when they construct a novel way of solving a mathematical proof, or when they generate and test hypotheses about mathematical constructs (Batey & Furnham, 2006; Bolden et al., 2010). Moreover, the ability of mathematicians to be creative has been identified as fundamental for the expansion of the mathematical field (Sriraman, 2004). Therefore, it is important to learn more about the theoretical and fundamental underpinnings of mathematical creativity as this may lead to more integration of creativity in this domain.

Haylock (1997) stated that the most common way of describing mathematical creativity encompasses the novel, original, or unique combination and rearrangement of mathematical strategies, elements, and techniques. Variations of this definition can also be found in other studies (Runco & Jaeger, 2012; Sriraman, 2005). More recently, the creativity indicators of fluency, flexibility, and originality have been combined with mathematical creativity, linking it to divergent thinking (Kim, Cho, & Ahn, 2004; Mann, Chamberlin, & Graefe, 2017). Fluency can be seen as the absolute number of responses formulated for a task or problem and is often seen as a kind of brainstorming. Hence, a high fluency score signals many responses or ideas were generated. Flexibility is the creative ability to think about a problem or a task from multiple perspectives or the ability to reverse mental processes. Oftentimes, people become "stuck" when working on a problem-solving task or multiple solution task because they perseverate on one type of perspective. This may be especially true for mathematics because in mathematics education often only one type of perspective is taught; therefore, children find it difficult to let go of these rules and strategies. This may leave children with a narrow view of mathematics as a subject with only right and wrong answers and a discipline in which it is important to get the right answers as fast as possible, in an automatic way, without thinking or effort (Ginsburg, 1996; Kolovou, Van den Heuvel-Panhuizen, & Bakker, 2009). Originality is the ability to create novel ideas and solutions that are unique in a given setting (e.g., for example a child may be the only one with a particular solution to a math problem in a class). This element of creativity is often the only type of creativity that is identified by teachers in their students (Mann et al., 2017).

Despite some criterion problems with mathematical creativity, researchers have established that creativity and mathematics are related in some way (Bolden et al., 2010; Kroesbergen & Schoevers, 2017; Leikin & Pitta-Pantazi, 2013). In fact, one study reported that creativity predicted a significant part of the variance in performance on mathematical tasks in children similar to the variance that was explained by working memory and number sense (Kroesbergen & Schoevers, 2017). However, these studies do not provide insight into the underlying cognitive processes that are involved in mathematical creativity or how this relation might differ for children with different mathematical abilities. Furthermore, these cognitive processes, such as executive functions and cognitive control, have not been studied in combination with creativity and mathematics or mathematical creativity before. Shedding a light on this relation could aid teachers and curriculum developers in promoting creativity in the classroom.

Executive functioning

Aside from the diminished role that creativity and divergent thinking have played in education compared to convergent thinking and routine tasks, the role of executive functions in education has in fact received much attention. This surge in attention can be attributed to the fact that good executive functioning skills predicts high achievement in education (e.g., Brock, Rimm-Kaufman, Nathanson, & Grimm, 2009; Miller, Müller, Giesbrecht, Carpendale, & Kerns, 2013; Yeniad, Malda, Mesman, IJzendoorn, & Pieper, 2013).

As mentioned briefly before, executive functions can be defined as the higher order cognitive processes that make it possible to adapt goal-directed behavior quickly and flexibly (Davidson, Amso, Anderson, & Diamond, 2006; Rhoades, Greenberg, Lanza, & Blair, 2011; Van der Sluis, De Jong, & Van der Leij, 2007). Many different components of executive functions have been described such as working memory, cognitive flexibility, planning, problem-solving, and impulse control (for a review, see Jurado & Rosselli, 2007). Miyake and colleagues (2000) identified three distinctly different executive functions: shifting, updating, and inhibition; although, these functions do show some overlap (see also: Lezak, 1982). *Shifting* is the ability to flexibly shift from one set of rules or tasks to another, for example shifting between math assignments that require addition to math assignments that require subtraction. *Inhibition* can be defined as the ability to inhibit a very salient and prepotent response, which is often not conductive to reaching a goal, in favor of another more appropriate response or no response at all. Finally, *updating* is the ability to be able to monitor working memory content and add or remove information from this content. In problem-solving situations, it is necessary to continuously update working memory with new information that might help solve the problem and to remove information from working memory that is no longer relevant for the task at hand (Cornoldi, Drusi, Tencati, Giofrè, & Mirandola, 2012).

Regarding the executive function updating, evidence from a meta-analysis suggests that this ability is most connected to mathematics in children who are typically performing (Friso-Van den Bos, Van der Ven, Kroesbergen, & Van Luit, 2013) and in children with mathematical learning difficulties (Geary, Baily, & Hoard, 2009). Some studies report that there is a relation between mathematics and inhibition (Bull & Scerif, 2010; Chamandar, Jabbari, Poorghorban, Sarvestani, Amini, 2019; Lee, et al., 2012; Passolunghi & Siegel, 2004); however, other studies do not find this connection (Miller et al., 2013). For example, Passolunghi and Siegel (2004) found that a group of children who experienced mathematical difficulties had worse working memory performance, especially for inhibiting irrelevant information, compared to a group of children without mathematical difficulties. Furthermore, children with reading or mathematical difficulties have been found to show low performance on working memory tasks that depend on adequate inhibitory performance (Chiappe, Siegel, & Hasher, 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Passolunghi & Siegel, 2001).

During the creative process, the executive function updating may be important to update working memory content with new incoming stimuli that might be relevant for the creative process and to remove previous solutions or incorrect answers (Zabelina, Friedman, & Andrews-Hanna, 2019). In addition, good shifting abilities also seem advantageous to facilitate the creative process. In fact, flexibility seems necessary for creativity by enabling a person to generate many different creative responses and switch between concepts and strategies with ease (Filippetti & Krumm, 2020; Pan & Yu, 2018). Furthermore, to increase both divergent and convergent thinking, it seems logical that shifting between different response sets will be beneficial. However, empirical evidence on this relation is scarce and does not reveal a clear picture yet (Benedek, Jauk, Sommer, Arendasy, & Neubauer 2014; Pan & Yu, 2018). Moreover, creativity and shifting or updating have not been examined before in children; although, it is important to glean which executive functions should be encouraged during primary school when we want to stimulate creative thinking. Results on the relation between inhibition and creativity are twofold. On the one hand, there is evidence that good inhibitory skills and other executive functions will be beneficial to creativity because it is necessary to focus and persist on what you are working on when creating something novel and original, be it a creative thought or a creative product (Benedek. Franz, Heene, & Neubauer, 2012; Burch, Hemsley, Pavelis, & Corr, 2006; Groborz & Necka, 2003). When inhibition skills are well developed, noise and irrelevant stimuli from the environment can be ignored, which prevents distractions and leaves more space in working memory content for information that is relevant to the current task or process. On the other hand, a negative relationship between inhibition and creativity has also been reported (Carson et al., 2003; Gonzalez-Carpio et al., 2017; Zabelina, Condon, & Beeman, 2014). An explanation for this might be that a broader range of information from the environment can reach consciousness and can be processed in working memory when inhibition is reduced (Carson et al., 2003). Thus, although reduced inhibition leads to inattention and distractibility, which in large quantities are a negative consequence, it can also increase the ability to perceive more or different affordances, which may be beneficial for creativity.

Selective attention, sensory gating, and sensorimotor gating

Pursuant to this idea is the disinhibition hypothesis (Eysenck, 1967). According to this hypothesis, a creative, excitatory state can be achieved when cortical arousal levels in the frontal regions of the brain are low. That is because these regions inhibit other areas of the brain according to EEG research (Martindale & Greenough, 1973; Martindale & Hines, 1975). Thus, if cortical activation is high, this will create a sort of state of focussed attention and high cognitive control in which remote association processes will be suppressed. On the other hand, if cortical activation is low, a state of disinhibition will be present, in which cognitive control and selective, focussed attention is decreased, therefore hypothetically creating a more hospitable environment for creative and divergent thinking. Support for this hypothesis comes from evidence found in neurocognitive research that revealed reduced control of frontal regions in adults with ADHD, which was associated with increased flexible thinking (Thompson-Schill, Ramscar, & Chrysikou, 2009). Similarly, maturation of the frontal regions of the brain was found to be slower in children with ADHD (Shaw et al., 2007).

Apart from one EEG study (Zabelina, O'Leary, Pornpattananangkul, Nusslock, & Beeman, 2015), the connection between early, subconscious cognitive markers of attention, such as sensory gating and creativity, has not been researched in a healthy population to our knowledge, especially not in children. Instead, most studies that link creativity to impaired attentional profiles involve patient populations (i.e., Green & Williams, 1999; White & Shah, 2006, 2011). For instance, in patients with schizophrenia several psychophysiological deficits have been suggested to be endophenotypic for this disease (e.g., Hoptman et al., 2004; Oranje, Aggernaes, Rasmussen, Ebdrup, & Glenthøj, 2013). Two of these psychophysiological measures are thought to assess different aspects of early stimulus filtering on a pre-attentive level, i.e., the prepulse inhibition (PPI) of the acoustic startle reflex and gating of the auditory evoked potential (P50 suppression), which will be discussed in more detail below.

When persons are presented with a weak stimulus, followed by an intense stimulus, a muted magnitude of the startle reflex will be found in comparison to if the intense stimulus is presented alone. This muted or inhibited magnitude of the startle reflex is called PPI and is a measure of sensorimotor gating. In research with human subjects, this startle response is commonly expressed as ([1-(PP/PA)]*100%), by calculating the percentage reduction of the average startle response to the prepulse-pulse trials compared to the average startle response to the pulse alone trials (Madsen, Bilenberg, Cantio, & Oranje, 2014). This modulation of PPI seems to be dependent on higher brain regions such as the (medial) prefrontal cortex and lower brain structures such as the limbic cortex, amygdala, and hippocampus (for a review, see Swerdlow, Geyer, & Braff, 2001), which modulate startle reflexes. Thus, the weak prepulse stimulus causes inhibition of the startle response to the second stimulus, albeit within certain time limits (interstimulus intervals [ISIs] ranging from approximately 30 to 1000 ms, with maximum PPI usually found with 120 ms ISIs).

Another way to measure psychophysiological gating of sensory input is with P50 suppression. To measure P50 suppression, a measure of sensory gating, people are presented with click-pairs of identical auditory stimuli with an ISI of 500 ms (e.g., Hammer, Oranje, & Glenthoj, 2007; Zabelina et al., 2015). Fifty ms after the second stimulus is presented, a reduced evoked response in comparison to the first stimulus can usually be observed around 50 ms, which is named the P50 suppression (Oranje, Geyer, Bocker, Kenemans, & Verbaten, 2006). This reduction in peak amplitude of the P50 ERP is assumed to be caused by the brain's conditioning due to the first stimulus, therefore "gating" the processing of the second stimulus. Although there are several theories about which brain regions are important for sensory gating, there is evidence that frontal and hippocampal regions are involved (Grunwald et al., 2003; Oranje et al., 2006). P50 suppression is known to be of a similar level in children and adults once children reach the ages between 10 and 14 years old (Myles-Worsley et al., 1996).

Later in the attentional process, after stimulus filtering, two conscious processes exist that may also affect creativity by causing variations in selective attention and cognitive control, reflected by the P300 amplitude and the N200 amplitude. Both ERPs are involved in stimulus evaluation. The N200 amplitude is a frontally located, negative ERP that is elicited around 200 ms post-stimulus in response to conflict or conflict monitoring (Donkers & Van Boxtel, 2004; Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof, 2003). For instance, when a different, deviant auditory stimulus is heard amongst a continuous stream of standard, regular auditory stimuli, an N200 amplitude will be present after the rare deviant auditory stimuli. About 300 ms after stimulus presentation, a positive ERP, the P300 amplitude, is elicited in response to memory and attentional aspects of stimulus processing (Friedman, Cycowicz, & Gaeta, 2001). The P300 amplitude is composed of two peaks: the first is named the P3a amplitude and is elicited when a distractor stimulus is observed. On the other hand, the P3b amplitude is related to attentional and cognitive control processes and has been related to task switching (Polich & Criado, 2006). The P3b amplitude is more parietal based in comparison to the more frontal P3a amplitude. Similar to the N200 amplitude, the P300 amplitudes have been suggested to reflect a conscious match-mismatch evaluation of stimuli in order to decide whether to respond or not (Smith, Johnstone, & Barry, 2008). As such, while both ERPs are related to selective attention and cognitive control, the N200 amplitude will be most prominent for deviant or rare trials, as they signal conflict, even when no response is required (Enriquez-Geppert, Konrad, Pantev, & Huster, 2010; Nieuwenhuis, et al., 2003). In contrast, the P300 amplitudes are related to processing the stimulus and memory evaluation (Polich, 2007).

Broadly speaking, there are two possible routes that might lead to higher creativity based on the disinhibition hypothesis (Eysenck, 1967). The first possibility is that less cortical activation leads to adaptations very early on in the attentional process, during sensory or sensorimotor gating. These filtering processes of the brain are subconscious and stimulus-driven and can therefore be described as "bottom-up." Creative, divergent thinking requires making numerous associations to increase the number of responses (diversification based on fluency and flexibility), which may benefit from a broader attentional filter (Chrysikou, 2019; Mayseless, Eran, & Shamay-Tsoory, 2015). Such a state of low filtering early in the attentional process may facilitate the bottom-up generation of ideas by increasing the number of stimuli that reach working memory, be it from the environment or from memory (Carson et al., 2003; Hommel, 2012). The second possible way that reduced cortical activation might lead to increased creativity is by adaptations in the "top-down" conscious, attentional filtering processes later in the attentional process. Hence, when cortical activation is reduced, lower brain areas will be less inhibited. This will create a state of reduced cognitive control and dispersed attention, which may promote creativity by reduced inhibition of remote association areas. However, to what extent this reduction in cortical activation might still be beneficial is also not clear. There are various accounts of creative genius in combination with some sort of mental illness connected to dysfunctional psychophysiological measures and a broadened attentional filter. Hence, there seems to be an optimum of distributed attention that can tip over to pathological levels such as those visible in patients with schizophrenia (e.g., Acar, Chen, & Cayirdag, 2018; Oranje & Glenthøj, 2013). Finally, some forms of creativity may profit more from reductions in cortical activation and (thus) cognitive control in comparison to others. That is, while some creative tasks in which having a flexible mindset might lead to more unusual and creative responses (Nijstad, De Dreu, Rietzschel, & Baas, 2010; Zhang, Sjoerds, & Hommel, 2020), the same cortical disinhibition might lead to too much distraction during convergent creative tasks or tasks that require focused attention for an extended period (Zhang et al., 2020).

Outline of the dissertation

The main aim of this PhD project was to unravel the underlying neural and cognitive aspects of (mathematical) creativity and to increase attention for creativity in education by showing that inattention and distractibility might also have its benefits.

This dissertation consists of several studies. In *Chapter 2*, the findings from our first study (*N* = 82) are described. We carried out this study to inspect whether inhibition moderated the relation between mathematical ability and mathematical creativity during a multiple solution task. We hypothesized that mathematical ability would be directly related to mathematical creativity. Due to inconsistent results from previous reports in the literature, we additionally hypothesized that inhibition does not have a direct relation with mathematical creativity but instead acts as a moderator between mathematical ability and mathematical creativity.

In *Chapter 3*, the main theoretical model about creativity, mathematics and executive functioning is discussed based on findings from our largescale behavioral study (*N* = 278). This study had a similar design to our first study that we carried out, described in *Chapter 2*. In this chapter, we used structural equation modelling to compare two path models with the goal to further our understanding of the role of executive functions in mathematical creativity. The first model examined if executive functions, domain-general creativity, and mathematical ability all influence mathematical creativity directly. The second model included two additional paths to check whether updating also influences mathematical creativity indirectly through its direct influence on mathematical ability and domain-general creativity.

In *Chapter 4* and *Chapter 5* we report our findings regarding the cognitive and neuroscientific factors related to creativity. With a psychophysiological test battery, we obtained EEG and EMG measures to investigate the role of sensory gating, sensorimotor gating, and cognitive control during a selective attention paradigm on a neural level to elucidate if such early neurological differences are related to creativity and attentional difficulties. In the study described in *Chapter 4*, we specifically focused on sensory gating (*n* = 65) and sensorimotor gating (*n* = 37), as early measures of leaky attention and psychophysiological gating, and compared results with our creativity and attentional measures. We hypothesized that reduced sensory gating and sensorimotor gating would be related to higher values of creativity and attentional difficulties because this would lead to a more diverse range of stimuli entering working memory to use creatively. In *Chapter 5* we focus more on cognitive control as measured by specific event related potentials during a selective attention paradigm (*N* = 62). Here we examined the relation between different measures of creativity, attentional difficulties, and cognitive control. On the one hand, we hypothesized that higher creativity scores and increased cognitive control are related. On the other hand, we hypothesized that more attentional difficulties would be related to reduced cognitive control during a selective attention paradigm. Additionally, we hypothesized that more attentional difficulties and higher creativity would be associated with an altered (subconscious) orienting reflex.

In *Chapter 6* an overview is given of our main findings presented in this dissertation. Results are discussed in light of their implications, and possible directions for future research are proposed.

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Inhibition, friend or foe? Cognitive inhibition as a moderator between mathematical ability and mathematical creativity in primary school students

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Abstract

It is still unclear which cognitive factors stand at the base of mathematical creativity. One factor could be inhibition, but results are inconsistent. A possible explanation is that this relation is more complex than the direct relations tested, until now. In the current study, the hypothesis was tested that cognitive inhibition moderated the relationship between mathematical ability and mathematical creativity. The sample included 82 primary school students between 8 and 12 years of age. Mathematical creativity was measured with a multiple solution task and scored on fluency, flexibility, and originality. While there was a direct relation between mathematical ability and mathematical creativity, inhibition did not have a direct effect on mathematical creativity, but it positively moderated this relationship for flexibility and originality. These results indicate that reduced inhibition strengthens the relationship between mathematical ability and mathematical flexibility and between mathematical ability and mathematical originality, but not the relation between mathematical ability and mathematical fluency. These findings are discussed in relation to children with high and low mathematical abilities, measurement of inhibition, and the domain-general/ domain-specific discussion of creativity.

Keywords: Mathematics; Creativity; Divergent thinking; Inhibition; Flexibility; Originality; Fluency

Introduction

Creativity has been identified as necessary to thrive in the 21st century (Bell, 2010), however, creativity is least promoted during primary school in the domain of mathematics (Bolden, Harries, & Newton, 2010; UNESCO, 2012). Since creativity is deemed important in reaching excellence in mathematics and in extending the domain (Sriraman, 2004; Sternberg & Lubart, 1999), mathematical creativity should be an important aspect of the mathematical curriculum. However, in contrast to mathematical abilities, it is less clear which cognitive factors play a role in mathematical creativity. Therefore, the current study investigated whether the executive function inhibition (i.e. suppressing irrelevant, prepotent, and bottom-up thoughts or stimuli in favor of other, more fitting information; Miyake et al., 2000) plays a role in mathematical creativity. Specifically, we tested the hypothesis that inhibition moderates the relationship between mathematical ability and mathematical creativity in primary school children.

Mathematical creativity

Mathematical creativity is commonly operationalized as divergent thinking in mathematical tasks and is often measured with a multiple solution task (Kattou, Kontoyianni, Pitta-Pantazi, & Christou, 2013; Leikin, 2009). In the current study, mathematical creativity thus refers to mathematical divergent thinking. However, for readability and adherence to related literature, it is described as mathematical creativity. Leikin and Lev (2013), for example, developed a mathematical creativity task and scored each answer on fluency (i.e. the number of answers), flexibility (i.e. the amount of strategies with different properties, representations, or mathematical domains), and originality (i.e. the answers of a participants compared to a reference group). Multiple solution tasks make it possible to look at the originality of an idea, which is a qualitative way of measuring creativity, and to examine the different ways in which mathematical assignments were solved, even when solutions are less original (i.e. flexibility; Silver, 1997), which is an important aspect of creativity, as well.

Mathematical ability

Mathematical ability (i.e. quantitative properties such as number sense and pre-algebraic reasoning, causal abilities which include cause and effect, spatial abilities such as perspective and spatial rotation, qualitative abilities such as examining differences and similarities, and inductive/deductive abilities which focus on reasoning problems; Kattou, Kontoyianni, Pitta-Pantazi, and Christou, 2013) is an essential prerequisite for mathematical creativity (Haavold, 2013) because as peoples' knowledge about a subject increases, they are able to connect more and different types of information, which will lead to more, different, and more original answers (Schoevers, Kattou, & Kroesbergen, 2018; Sheffield, 2009). In other words, previously learned mathematical knowledge is the scaffolding on which novel mathematical solutions are formed

(Nakakoji, Yamamoto, & Ohira, 1999) and will also determine how new mathematical knowledge and assignments will be approached (Sheffield, 2009).

Inhibition

Although it is clear that executive functions (i.e. higher cognitive functions that regulate thoughts and behaviors) are important during mathematics (as found by Friso-Van den Bos, Van der Ven, Kroesbergen, and Van Luit, 2013 in a meta-analysis on elementary education children), it is not clear what role they play in mathematical creativity. Executive functions are especially useful during unfamiliar, novel situations which possibly make them an important aspect of creativity, as well.

In the current study, we focus on the executive function inhibition. At face value, it seems as if (mathematical) creativity relies upon adequate inhibition, by inhibiting common answers and increasing the fluent generation of ideas (Benedek, Franz, Heene, & Neubauer, 2012; Golden, 1975; Groborz & Nęcka, 2003; sample ages 14–25). However, evidence that reduced inhibition leads to increased creative performance or that inhibition and creativity are unrelated has been found in adult studies (Burch, Hemsley, Pavelis, & Corr, 2006; Stavridou & Furnham, 1996). Reduced inhibition may facilitate creativity by broadening a person's attentional range and increasing the amount of unfiltered stimuli that gain access to working memory. However, since the age range of the reported studies is very heterogeneous and mostly focuses on adolescents and adults, it is difficult to generalize these findings to a child sample.

In addition, the predictive value of inhibition on mathematics is also still under debate. For example, it has been found that for 3–18 year-olds, inhibition has a unique contribution to mathematical abilities (Harvey & Miller, 2017; Kroesbergen, Van Luit, Van Lieshout, Van Loosbroek, & Van de Rijt, 2009; Sikora, Haley, Edwards, & Butler, 2002). However, another study, with 5–8 year olds, reported that mathematical ability and inhibition are only partially related (Toll, Van der Ven, Kroesbergen, & Van Luit, 2010). Moreover, there are even results that indicate the two are unrelated in 6–10 year olds (Censabelle & Noël, 2007; Lee et al., 2012).

To excel in mathematics, flexible thinking and the ability to examine a mathematical situation from different angles are necessary (Dreyfus & Eisenberg, 1996), which are common characteristic of creativity (Batey & Furnham, 2006). However, despite these claims and inconsistent results, the relationship between mathematical abilities, mathematical creativity, and cognitive inhibition has not been studied before (to our knowledge), especially not in children. Furthermore, the inconsistency of previous results makes it difficult to formulate a clear hypothesis. Therefore, we hypothesized that better mathematical abilities lead to better performance on a mathematical creativity task and that inhibition influences this relationship.

Methods

Participants

We investigated a convenience sample of 92 Dutch primary school students from grade 3 to 5. After exclusions, based on missing and extreme values, the final sample was composed of 80 participants for measures of fluency (38 boys, M_{age} = 9.95 SD_{age} = 0.84, post-hoc power = 0.77); 82 participants for flexibility (41 boys, M_{age} = 9.93 SD_{age} = 0.82, post-hoc power = 0.93); and 81 participants for originality (41 boys, M_{age} = 9.96 SD_{age} = 0.82, post-hoc power = 0.95).

Measures

Inhibition. Inhibition was measured with an adapted version of the Flanker task, the Fish Game, in which the direction of the middle target has to be identified (Eriksen & Eriksen, 1974). This target is flanked by four identical targets that cause distraction when they are in the opposite direction (i.e. incongruent trials) or facilitate identification when they are in the same direction (i.e. congruent trials), as can be seen in Fig. 1. The task consisted of 5 practice trials, in which the participant received feedback on their responses, followed by 12 congruent trials, 12 incongruent trials, and 12 neutral trials (i.e. in which only one fish was presented and there were no flanking fishes). Stimuli were randomly selected and presented at the top or the bottom of the screen. Inhibition was measured by subtracting the reaction time of the neutral trials from the incongruent trials, thereby subtracting general processing speed. The Fish Game has medium to good internal consistency (in this study: Cronbach's α is between 0.56 and 0.79).

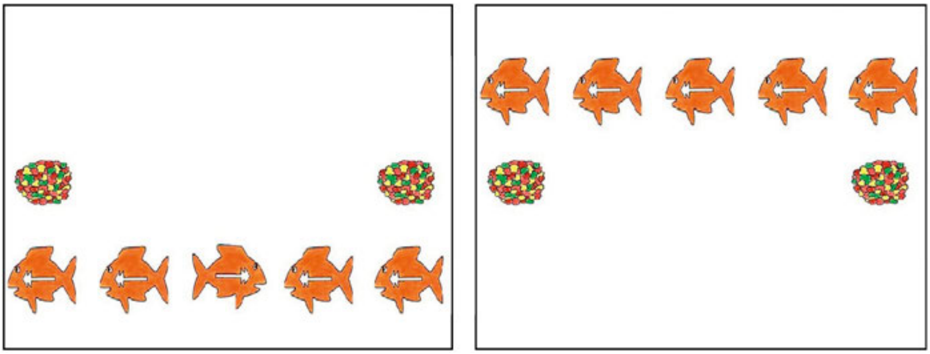

Figure 1. Example of an incongruent (right) and congruent (left) trial of the Fish Game.

Mathematical ability. The Cito test is the standard test battery used by most Dutch primary schools to monitor spelling, vocabulary, reading comprehension, and mathematical development (Janssen, Scheltens, & Kraemer, 2007). The mathematical part of the Cito consists of several mathematical categories (e.g. arithmetic, measuring, fractions, percentages, and proportions), adjusted for the level of mathematical ability in each grade. An example question in the category percentages is: '*With a 50% discount the new price is €1.95. What was the old price?*' For the current study, only the ability sumscores on the Cito math-test were relevant, which have a good reliability (between 0.91 and 0.94 for grades 3 and 5; Janssen, Verhelst, Engelen, & Scheltens, 2010).

Mathematical creativity. To measure mathematical creativity, we used an adapted version of the Mathematical Creativity Test (Kattou et al., 2013; Dutch translation: Schoevers et al., 2018) with five multiple-solution mathematical questions. This test has good internal consistency (Cronbach's α 0.78). Participants have to construct as many solutions as they can that are distinct from each another. We used three mathematical tasks from the original task and added one additional task from Hershkovitz, Peled, and Littler (2009) about dividing a pie in such a way that four people would get the same amount. This task had the following instruction: '*Four children [names given] have to share a square cake fairly. How will they cut the cake?*'. Answers were scored on fluency, flexibility (maximum score = 22), and originality (maximum score = 1 for each questions).

Procedure

The students were tested during two 1-hour sessions in 2 days. Prior to the study, we received ethical approval from the Faculty Ethics Review Board of Social and Behavioural Sciences (FERB16-112), and active informed consent from at least one parent of the participating child. On the first day, individual paper-and-pencil tasks were administered in a classroom setting, amongst which was the mathematical creativity task. On the second day, computer tasks to measure executive functioning were administered in groups of six participants under the supervision of a researcher, alongside a paper-and-pencil task.

Data analysis

We utilized hierarchical multiple regression analysis to assess the relationship between mathematical creativity, mathematical ability, and cognitive inhibition, with age in block one, mathematical ability and inhibition in block two, and the moderator variable mathematical ability × inhibition in block three. This process was repeated three times to investigate this relationship for outcomes of fluency, flexibility, and originality. The significance alpha level was set at $p < .05$ (two-tailed) and the t-statistic was used to test if predictors were significant contributors. Standardized scores ($M = 0$, $SD = 1$) were used in the analyses to avoid multicollinearity and ease interpreting the magnitude of effects.

Results

Table 1 shows the descriptive statistics and Table 2 shows the correlations per mathematical creativity outcome, which show that mathematical ability was significantly correlated with flexibility, fluency ($p < .001$), and originality ($p < .01$) and that flexibility ($p < .02$) and originality ($p < .05$) were significantly correlated with the interaction-term between inhibition and mathematical ability. The multiple regression results are depicted in Table 3.

Table 1 *Descriptive statistics for Mathematical Ability, Flexibility, Fluency, Originality, and Inhibition.*

	Variable	*M*	*SD*	*Min*	*Max*
Flexibility	Age	9.93	0.83	8.38	11.39
(*n* = 82)	Mathematical Ability	0.06	0.90	-2.55	2.47
	Inhibition RT (ms)	244.49	401.44	-824.00	2573.67
	Flexibility	6.94	1.74	1	10
Fluency	Age	9.92	0.85	8.38	11.39
(*n* = 80)	Mathematical Ability	-0.01	0.90	-2.55	2.47
	Inhibition RT (ms)	238.63	404.50	-824.00	2573.67
	Fluency	18.14	13.08	5	90
Originality	Age	9.93	0.84	8.38	11.39
(*n* = 81)	Mathematical Ability	0.15	0.89	-2.55	2.47
	Inhibition RT (ms)	244.38	404.16	-824.00	2573.67
	Originality	1.81	0.54	0.2	2.8

Note. The variable Mathematical Ability consists of standardized scores. RT = reaction time.

Table 2 *Correlations of Flexibility, Fluency and Originality with Age, Mathematical Ability, Inhibition and Mathematical Ability × Inhibition.*

	Age	Mathematical Ability	Inhibition RT (ms)	Mathematical Ability x Inhibition
Flexibility	-.085	.522***	-.018	.261*
Fluency	.147	.391***	-.023	.019
Originality	.026	.372**	-.050	.255*

Note. Scores are standardised. RT = mean reaction time
*$p < .05$. ** $p < .01$.*** $p < .001$.

Table 3 *Hierarchical Regression Models for Flexibility, Fluency, and Originality Predicted from Mathematical Ability, Inhibition, and Mathematical Ability × Inhibition, Corrected for Age.*

		Predictor	B	SE B	b	*t*	*p*
Flexibility	Model 1	Constant	.951	1.297		.733	.466
		Age	-.099	.130	-.085	-.759	.450
	Model 2	Constant	.605	1.124		.538	.592
		Age	-.067	.113	-.058	-.597	.552
		Mathematical Ability	.557	.104	.520	5.373	<.001
		Inhibition	.016	.105	.015	.153	.879
	Model 3	Constant	.730	1.089		.670	.505
		Age	-.078	.109	-.067	-.716	.476
		Mathematical Ability	.541	.101	.505	5.382	<.001
		Inhibition	.071	.104	.065	.680	.499
		Mathematical Ability x Inhibition	.252	.100	.240	2.511	.014
Fluency	Model 1	Constant	-1.386	.944		-1.468	.146
		Age	.124	.095	.147	1.309	.194
	Model 2	Constant	-1.585	.877		-1.808	.075
		Age	.143	.088	.170	1.631	.107
		Mathematical Ability	.319	.083	.401	3.853	<.001
		Inhibition	.006	.083	.008	.075	.941
	Model 3	Constant	-1.593	.883		-1.803	.075
		Age	.144	.088	.170	1.627	.108
		Mathematical Ability	.320	.083	.403	3.832	<.001
		Inhibition	.003	.085	.003	.031	.976
		Mathematical Ability x Inhibition	-.016	.082	-.021	-.193	.847
Originality	Model 1	Constant	-.387	1.238		-.313	.755
		Age	.029	.124	.026	.233	.817
	Model 2	Constant	-.420	1.164		-.361	.719
		Age	.030	.117	.027	.259	.796
		Mathematical Ability	.382	.109	.371	3.501	.001
		Inhibition	-.028	.108	-.027	-.258	.797
	Model 3	Constant	-.376	1.140		-.330	.742
		Age	.027	.114	.024	.237	.814
		Mathematical Ability	.361	.107	.350	3.363	.001
		Inhibition	.021	.108	.021	.197	.845
		Mathematical Ability x Inhibition	.219	.105	.223	2.091	.040

Mathematical ability, but not inhibition, accounted for a significant amount of variance in flexibility ($R^2 = 0.276$, $F(3, 78) = 9.894$, $p < .001$) and in fluency ($R^2 = 0.182$, $F(3, 76) = 5.623$, $p < .001$). Similarly, for originality, mathematical ability, but not inhibition, accounted for a significant amount of the variance ($R^2 = 0.374$, $F(3, 77) = 4.117$, $p < .01$).

The interaction term accounted for a significant proportion of the variance in flexibility ($\Delta R^2 = 0.055$, $\Delta F(1, 77) = 6.307$, $p < .02$, b = 0.252, $t(77) = 2.51$, $p < .02$) and originality ($\Delta R^2 = 0.049$, $\Delta F(1, 76) = 4.374$, $p = .04$, $b = 0.219$, t(76) = 2.09, $p < .05$), but not in fluency ($\Delta R^2 = 0.00$, $\Delta F(1, 75) = 0.037$, $p = .847$, $b = -0.016$, $t(75) = -0.193$, $p = .847$).

Lastly, to further examine the direction of the moderation effect for groups with good and reduced inhibition, we examined the simple slopes, which can be viewed in Fig. 2, by subtracting the standard deviation (i.e. 1) from the centred inhibition and mathematical scores to create the high inhibition group and high mathematical group, and adding the standard deviation (i.e. 1) to the centred inhibition and mathematical scores to create the low inhibition group and low mathematical group.

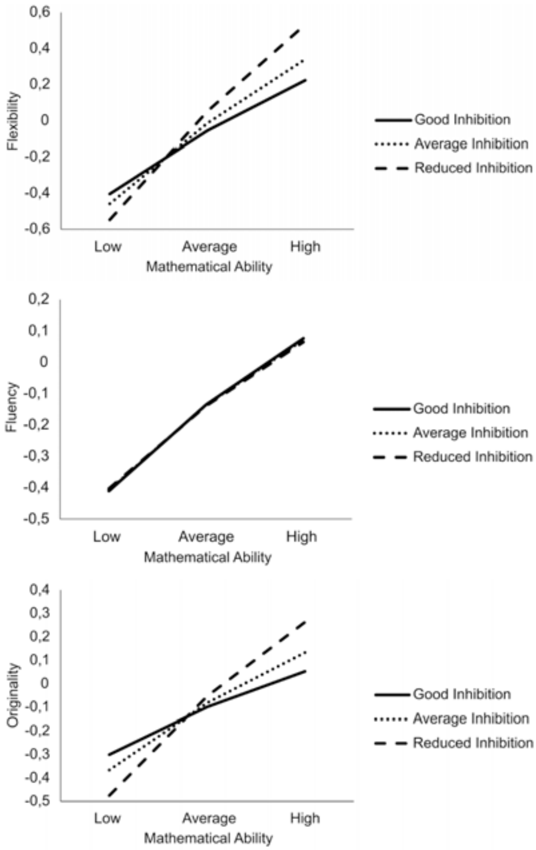

Figure 2. The influence of mathematical ability on measures of mathematical creativity for participants with good, average, and reduced inhibition.

For flexibility, results indicated that with good inhibition, mathematical flexibility only marginally increased as mathematical ability increased ($t(77) = 1.98$, $p = .052$). However, when inhibition was average (i.e. as in the original regression analysis), mathematical flexibility increased as mathematical ability increased ($t(77) = 5.38$, $p < .001$), and this effect was even larger for reduced inhibition ($t(77) = 5.77$, $p < .001$).

For originality, results indicated that with reduced inhibition scores, mathematical originality did not increase when mathematical ability increased ($t(76) = 0.91$, $p = .368$). However, for average inhibition scores, mathematical ability did have a positive effect on mathematical originality ($t(76) = 3.36$, $p < .001$), and this effect was even stronger for good inhibition scores ($t(76) = 4.07$, $p < .001$).

Discussion

The current study investigated whether cognitive inhibition moderated the relationship between mathematical ability and mathematical creativity. As hypothesized, results indicate that mathematical creativity depends on mathematical abilities and that reduced inhibition led to a stronger relationship between mathematical ability and mathematical creativity for the originality and flexibility of students' answers. The current results offer a new perspective on inhibition as a moderator, which is a valuable addition to previous creativity research that reported either positive or negative direct relationships between cognitive inhibition and creativity (Burch et al., 2006; Edl, Benedek, Papousek, Weiss, & Fink, 2014; Groborz & Nęcka, 2003).

It appears that children with low mathematical abilities and reduced inhibition have a double impairment in the sense that they do not possess enough mathematical abilities to imagine original, flexible, and creative solutions, which makes the task-demands higher for this group. In addition, they may experience more issues with the (increased) task-demands because of their reduced inhibition (Gilhooly, Fioratou, Anthony, & Wynn, 2007). These children probably show a limited range and persistency of solution-categories because of their limited mathematical abilities. Additionally, they may have difficulty inhibiting the most obvious answer, previous answers, and incorrect answers (Gilhooly et al., 2007). Similarly, inhibition has previously been linked to general mathematical (dis)ability as well (Harvey & Miller, 2017; Kroesbergen et al., 2009; Sikora et al., 2002). Thus, for children with low mathematical abilities, reduced inhibition does not seem to facilitate creativity.

On the other hand, reduced inhibition does have a positive influence on mathematical creativity for children with high mathematical ability. These children have an extensive repertoire of mathematical abilities, which probably lowers task-demands during mathematical multiple-solution tasks. Furthermore, it has been proposed that creative people attend to, at first sight, irrelevant stimuli (i.e. over-inclusive thinking because of reduced inhibition), which they can use to generate more original answers (Howard-Jones & Murray, 2003). In combination with increased mathematical ability, this may lead to the availability of different strategies, knowledge, and other stimuli in working memory that can be combined in such a way that solutions are more original and creative. Thus, reduced inhibition strengthens the relationship between knowledge and creativity in children with high mathematical abilities by letting them be more flexible and original. This is in line with Silver (1997), who emphasized the importance of deep, flexible knowledge during creative acts. In contrast, high fluency might be more related to intelligence (Lee & Therriault, 2013). Thus, it is perhaps better to focus on originality and flexibility when examining creativity because of their qualitative nature, whereas fluency is quantitative (Stavridou & Furnham, 1996).

Strengths and limitations

To our knowledge, the current study is the first to investigate inhibition as a moderator, within the domain of mathematics, in a primary school setting. Often, studies about the relation between creativity and inhibition only report correlational effects or analysis of variances, and the exact influence of the variables remains unknown (e.g. Burch et al., 2006; Stavridou & Furnham, 1996; Vartanian, Martindale, & Kwiatkowski, 2007). By using hierarchical multiple regression analyses, we provide more detail by adding multiple predictors to the model.

However, the current study also has some limitations. For example, originality was calculated based on all answers of the sample, which may differ greatly from sample to sample, and the originality score is dependent on sample size (Silva, 2008). Thus, investigating a broad range of creativity measures is advised in the future.

Additionally, accuracy of inhibition responses was not investigated because there was no response deadline during the task, which led to a ceiling effect of accuracy of nearly one. According to other studies, we thus only used the mean reaction time (e.g. Burch et al., 2006; Stavridou & Furnham, 1996; Toll et al., 2010). Although it does not seem as if omitting accuracy is a cause for concern, examining both accuracy and reaction time in future studies would increase the reliability of results and provide additional knowledge.

Future directions and implications

It appears that reduced cognitive inhibition (i.e. more distributed attention) is beneficial for the original and flexible use of mathematical abilities during multiple-solution tasks if there is a solid mathematical knowledge base to build on. However, if children have lower mathematical abilities and reduced inhibition, these two factors amplify each other, standing in the way of mathematical creativity.

By further examining the effect of inhibition in combination with low and high mathematical ability, we made it possible to take a closer look at the effect that cognitive inhibition has on mathematical creativity, providing a more detailed image and greater clarity concerning the inconsistent results thus far. Therefore, our results may not be as contradictory to previous findings as they seem. For instance, previous research regarding inhibition and creativity investigated different domains or domain-general creativity (e.g. Benedek et al., 2012; Burch et al., 2006). Since we investigated domain-specific creativity in the domain of mathematics, our results form an addition instead of a contradiction to existing literature and may further encourage researchers to investigate the relation between domain-specific creativity and other measures. Perhaps the effect inhibition has on creativity is as highly domain-specific as it is task-dependent (Wöstmann et al., 2013). For example, it has been suggested that task-demands in inhibition tasks can cause large differences in results and even reverse correlational effects (Vartanian et al., 2007). Another explanation may be found in the developmental path of inhibition. That is, inhibition plateaus around the age of 11 (Huizinga & Van der Molen, 2007). This may mean that there are (individual) differences in how well children can implement their inhibition during a creativity task before this age.

Often, reduced inhibition and higher distractibility are frowned upon, and focused attention and good inhibitory skills are seen as crucial for successful learning (Espy et al., 2004). However, our results suggest that these skills can lend a helping hand in tasks that demand flexibility and originality if children possess enough domain-specific knowledge and skills that they can creatively apply. Since the current study investigated a specific age range, future studies should investigate this further with different age ranges, as well as investigate the involvement of other executive functions and examine if these results are transferable to other domains of creativity, as well.

Conclusion

To conclude, in the pursuit of (mathematical) creativity, good inhibition seems more of a foe than a friend in regards to the flexibility and originality of imagined ideas from pre-existing mathematical abilities for children with high mathematical ability. However, inhibition seems to be a friend for children with low mathematical abilities. This is the first time this has been researched in children, and it may lead to an encouragement of distributed attention and creativity during development and differentiated education.

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3

The contribution of executive functions in predicting mathematical creativity in typical elementary school classes: A twofold role for updating

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Abstract

The goal of the current study was to investigate the role of executive functions in mathematical creativity. The sample included 278 primary school children (ages 8–13). Two models were compared: the starting model tested whether executive functions (shifting, updating, and inhibition), domain-general creativity, and mathematical ability directly predicted mathematical creativity. The second model, which fitted the data best, included the additional assumption that updating influences mathematical creativity indirectly through mathematical ability and domain-general creativity. Updating was positively related to mathematical creativity. Additionally, updating was positively related to mathematical ability and domain-general creativity. Inhibition, shifting, domain-general creativity and mathematical ability did not have a significant contribution to either model but did positively correlate with mathematical creativity. This study reports the first empirical evidence that updating is a predictor of mathematical creativity in primary school children and demonstrates that creativity is a higher order cognitive process, activating a variety of cognitive abilities.

Keywords: Creativity; Mathematics; Executive functions; Updating; Shifting; Inhibition; Divergent thinking

Introduction

It is of no doubt that creativity is important in mathematics (Sriraman, 2004). For example, some mathematical questions can be answered in multiple ways or require out-of-the-box thinking (Leikin & Pitta-Pantazi, 2013). Therefore, creativity should be encouraged and taught during primary school. However, teachers are unsure about how to incorporate creative exercises into their teaching methods, especially in the field of mathematics (Kaufman & Baer, 2004). From this perspective, research into creativity and mathematics has increased over the last years (Singer, Sheffield, & Leikin 2017), but mainly in adults or secondary school students, and much is still unknown. In particular, how executive functions are related to the domain of mathematical creativity remains unresearched. Executive functions, or the higher cognitive order functions that are necessary to reach a goal or finish a task, are important for the development and acquisition of mathematical ability. In addition, since executive functions are mainly important in novel, challenging situations in which flexibility is a key aspect (Davidson, Amso, Anderson, & Diamond, 2006; Rhoades, Greenberg, Lanza, & Blair, 2011; Van der Sluis, De Jong, & Van der Leij, 2007), they also seem to fulfill an important role during creative tasks (e.g., Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014; Sharma & Babu 2017). Domain-general creativity and mathematical ability, in their turn, seem to promote mathematical creativity (e.g., Jeon, Moon, & French, 2011; Kroesbergen & Schoevers 2017; Lin & Cho 2011; Sak & Maker 2006). To move beyond such correlational results and provide a more holistic image, the current study investigated if and how executive functions, domain-general creativity, and mathematical ability are related to mathematical creativity in a sample of 8- to 13-year-olds.

Domain-general creativity and mathematical ability in relation to mathematical creativity

Although creativity knows many definitions, a common description of the general creative process is that it is an “interaction among aptitude, process, and environment by which an individual or a group produces a perceptible product that is both novel and useful as defined within a social context” (Plucker, Beghetto, & Dow, 2004, p. 90). That a more general type of creativity is required in order to be mathematically creative has been reported in several studies (Ayllón Gómez, & Ballesta-Claver, 2016; Kroesbergen & Schoevers, 2017; Lin & Cho, 2011; Sak & Maker, 2006; Schoevers, Kroesbergen, & Kattou, 2018). These studies verify that there is a domain-general part of creativity, perhaps related to insight or divergent thinking (Mumford & Gustafson, 1988; Plucker, 1999). However, as others have found, most variance is explained by specific abilities (Chen, Himsel, Kasof, Greenberger, & Dmitrieva, 2006; Leikin, 2014; Sawyer, 2006). For instance, a very creative mathematician is not necessarily creative in another domain such as writing.

For example, Lin and Cho (2011) found that there was a direct effect of domain-general creativity on mathematical creativity, whereas variables such as motivation and environment only showed an indirect effect. Similar to the definition problem of creativity in general, the concept of mathematical creativity has also been operationalized in various ways (Mann, 2006; Sriraman, 2005). In the current study, mathematical creativity is used as a synonym for mathematical divergent thinking, in accordance with other work on this topic, and given the focus of the current study (e.g., Kattou, Kontoyianni, Pitta-Pantazi, & Christou, 2013; Leikin, 2009; Stolte, Kroesbergen, & Van Luit, 2019). In other words: mathematical creativity is the simultaneous activation of multiple ideas and sources of information in order to select and assemble several alternative solutions for mathematical tasks. Given the open nature of divergent thinking tasks, mathematical creativity is often associated with mathematical problem solving (Sriraman, 2005). Some mathematical tasks cannot be answered with standard or pre-learned strategies. For these tasks, creativity is important because more than one answer can be correct or more than one strategy can be used to find an answer (Leikin & Pitta-Pantazi, 2013). Mathematical creativity tasks are commonly scored on fluency (the number of correct answers), flexibility (the different strategies used or answer-categories), and originality (how unusual an answer is) (Sak & Maker, 2006; Schoevers et al., 2018). This differentiation provides both a quantitative and a qualitative measure of creativity.

Apart from domain-general creativity, domain-specific skills and proficiency (i.e., mathematical abilities such as spatial abilities, algebraic reasoning, and number sense) (Kattou et al., 2013) are also related to mathematical creativity. In order to be creative in a domain, a person needs to have at least some familiarity with this domain to use creatively (Csikszentmihalyi, 1997; Jeon et al., 2011; Sak & Maker, 2006). Empirical research supports this claim (Hong & Aqui, 2004; Mann, 2005; Sak & Maker, 2006; Schoevers et al., 2018; Stolte et al., 2019).

In comparison, the relation between domain-general creativity and mathematical ability is less straightforward. For instance, Schoevers et al. (2018) found that mathematical ability and domain-general creativity were not significantly related in a sample of fourth graders. Interestingly, their study showed that mathematical ability and domain-general creativity explained an almost similar amount of variance of mathematical creativity. They reported that creativity may not be a general construct of mathematical ability but may instead be domain-specific for mathematical creativity (Baran, Erdogan, & Çakmak, 2011; Schoevers et al., 2018). On the other hand, a positive relation between domain-general creativity and mathematical ability has been reported in a previous study, too. In this study, with 8-, 9-, and 10-year-olds, domain-general creativity predicted a similar amount of variance in mathematical ability as updating and number sense did (Kroesbergen & Schoevers 2017).

Executive functions and mathematical ability

A longstanding line of research shows the relation between executive functions and mathematical abilities. In such research, executive functioning is often divided into three processes: updating, shifting, and inhibition (or response inhibition) (Bull & Scerif, 2001; Cragg & Gilmore, 2014; Toll, Van der Ven, Kroesbergen, & Van Luit, 2011). Updating can be defined as the ability to continuously add and remove information from working memory storage as well as monitoring this process (Miyake et al., 2000). This function is important during a variety of everyday activities that involve several steps such as cooking, driving, and writing. Shifting refers to the ability to change strategies or shift from a set of rules to another; for instance, when changing between adding or multiplying numbers every other time. Response inhibition is characterized as the ability to stop an impulsive response and opt for a more appropriate response given the circumstances but also to inhibit immature strategies that are no longer optimal (e.g., when solving a mathematical assignment). Although the different executive functions are known to overlap, they each have unique properties (Miyake et al., 2000; De Ribaupierre & Lecerf, 2017). Therefore, we will study them separately in the current study, whilst accounting for their possible correlation.

In mathematics, updating is required to extrapolate the individual parts from a whole and to simultaneously add new information to the mix. These are important aspects of successful mathematical reasoning (Friso-Van den Bos, , Van der Ven, Kroesbergen, & Van Luit, 2013; Kroesbergen & Van Dijk 2015; Lee et al., 2012; Raghubar, Barner, & Hecht, 2010; Van der Ven et al., 2012). In addition, updating allows for the storage of intermediate results in working memory that can be manipulated to find the end-solution during a mathematical task (Van der Ven, Kroesbergen, Boom, & Leseman, 2012). Similarly, well developed shifting abilities are necessary when changing strategies during more advanced mathematical tasks (Agostino et al., 2010; Bull & Scerif, 2001; Yeniad et al., 2013). However, when the shared variance with updating is accounted for, the relation between shifting and mathematics may not be present anymore (Espy et al., 2004; Van der Sluis, De Jong, & Van der Leij, 2004; Van der Ven et al., 2012). For the third executive function, inhibition, the relation with mathematics seems comparable. Good inhibitory skills make it possible to inhibit immature strategies and irrelevant knowledge from entering working memory. Moreover, good inhibition is also necessary to stay focused on a task, and several studies find a positive relation between the two (Chiappe, Hasher, & Siegel, 2000; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998; Passolunghi & Siegel, 2001) but others do not support this relation (Lee et al., 2012; Van der Sluis et al., 2004; Van der Ven et al., 2012). Seemingly, updating may also be involved in inhibition and shifting, by keeping information online to manipulate in working memory (Van der Ven et al., 2012).

Executive functions and (mathematical) creativity

Executive functions are indispensable for the flexible adaptation of skills and knowledge, especially in novel situations (Dajani & Uddin, 2015). Given these characteristics, it seems plausible that they are linked to creativity as well. In the current study, we defined domain-general creativity as those creative abilities that are transferable across domains, similar to the intelligence factor g (Baer, 2012; Chooi, Long, & Thompson, 2014). Moreover, it may be that executive functioning and intelligence are related but unique concepts. For instance, one study found that only updating was a significant predictor of intelligence in young adults (Friedman et al. 2006). In a study about the unity and diversity of intelligence and executive functions in children between 7 and 9 years of age, a similar result was found (Brydges, Reid, Fox, & Anderson, 2012). Additionally, there are also indications that both inhibition and updating predict intelligence (Duan, Wei, Wang, & Shi, 2010) and that shifting predicts intelligence (Purić & Pavlović, 2012). Other studies found no such predicting effect of executive functions on intelligence (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003). This failure to find a relation was probably due to statistical decisions. In their study, Brydges et al. (2012) found a large overlap in variance between executive functioning and intelligence (between 69% and 80%). It has therefore been argued that, at least for children, what is measured during intelligence tests is not that different from the engagement of executive functioning (Brydges et al., 2012). Therefore, the current study placed its focus on executive functioning.

When creativity is required, it is important that different elements from the environment and from memory are connected even when they are not always obviously relevant at first. With this (uncommon) combination of elements, an original and creative idea can be generated. In order to do this, working memory needs to be continuously updated with new and/or different information. This leads to a broader scope of ideas and action possibilities. Therefore, a positive relation between creativity and updating can be expected (Benedek et al., 2014; Diamond, 2013).

In addition, it is important to shift one's focus from standard answers and concepts towards more novel ideas when thinking creatively. In this way, shifting also seems to be important to boost creativity by promoting flexibility (Nusbaum & Silvia, 2011; Pan & Yu, 2018). Surprisingly, empirical evidence for a positive relation between shifting and creativity is lacking and the only two studies reporting on this association found opposite results (Benedek et al., 2014; Pan & Yu, 2018). Although (cognitive) flexibility is often mentioned as one of the cornerstones of creativity such as in the dual pathway model of creativity (Nijstad, De Dreu, Rietzschel, & Baas, 2010; Stein, 1953; Torrance, 1974), only one empirical study supports this claim (Pan & Yu, 2018). This study by Pan and Yu (2018) only measured shifting and no other executive functions, whereas Benedek et al. (2014) took updating and inhibition into account as well. Perhaps the explanation that once several executive functions are taken into account, the explained variance from shifting is not significant anymore also applies for the relation between creativity and shifting.

Besides, good response inhibition and creativity have also been linked in the past (Benedek et al., 2014; Cassotti, Agogué, Camarda, Houdé, & Borst, 2016; Edl, Benedek, Papousek, Weiss, & Fink, 2014). Effective inhibition helps to suppress the increasing interference of previous responses in order not to persevere on initial ideas. There are also indications that good inhibition makes it difficult to move beyond less creative answers and think out-of-the-box (Burch, Hemsley, Pavelis, & Corr, 2006; Carson, Peterson, & Higgins, 2003; Scibinetti, Tocci, & Pesce, 2011). However, these studies refer to an early type of inhibition, namely latent inhibition, and thus, creativity may benefit from decreased early inhibition and well-developed response inhibition. Thus, with lowered latent inhibition, a more diverse collection of stimuli is available to a person, which leads to different and perhaps more original action possibilities (Carson et al., 2003). Response inhibition, on the other hand, needs to be sufficient to stay focused on the task at hand and move beyond less creative responses. Although there are a handful of studies that report on the effect of executive functions on domain-general creativity, these studies have investigated adult samples and did not always take the shared variance of executive functions into account. In addition, empirical evidence about the relation between executive functions and mathematical creativity is missing. It is important to understand what cognitive abilities are involved during mathematical creativity in children in order for teachers to feel more confident about incorporating creativity in their math lessons (Kaufman & Baer, 2004).

The current study

Even though previous studies have demonstrated that there are (mostly positive) relations between domain-general creativity, mathematical abilities, and mathematical creativity, to our knowledge, these factors have never been combined in a model with executive functions before or examined together in a sample of primary school children. Therefore, the current study aimed to create a theoretical model about the roles of the executive functions on domain-general creativity, domain-specific mathematical ability and mathematical creativity in primary school children. With this, we seek to transcend the correlational results that have been reported thus far and provide an integrated image of what underlying cognitive and behavioral factors are involved in mathematical creativity. Visual representations of our hypothesized models are presented in Figure 1 and Figure 2. Based on our discussion of the literature, we assumed that (1) domain-general creativity and mathematical ability would have a positive relation on mathematical creativity; (2) the executive function updating would have a positive relation to mathematical ability and domain-general creativity, but also to mathematical creativity; and (3) inhibition and shifting would be directly and positively related to mathematical creativity. Although there are indications that shifting and inhibition do not explain additional variances in mathematics and (general) creativity once the shared variance with updating is accounted for, no such evidence is present within the domain of mathematical creativity (Benedek et al., 2014; Espy et al., 2004; Van der Sluis et al., 2004). Indeed, given the theoretical link between shifting and creativity, we wanted to hypothesize a positive link between the two for mathematical creativity.

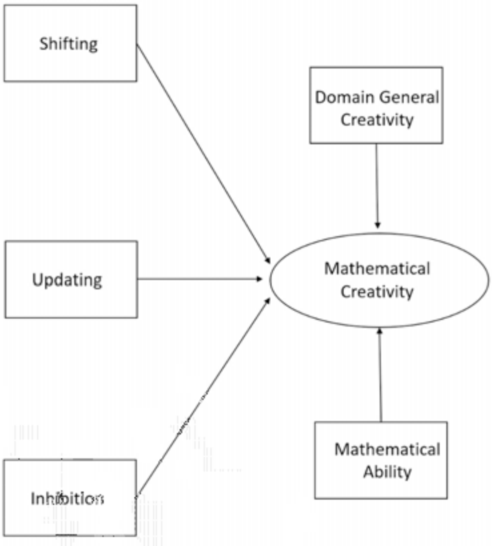

Figure 1. Theoretical model in which mathematical ability, domain-general creativity, shifting, updating, and inhibition all directly influence mathematical creativity.

Note. To increase clarity, this image does not show error-terms or that we correlated the errors of the executive functions to account for their overlap.

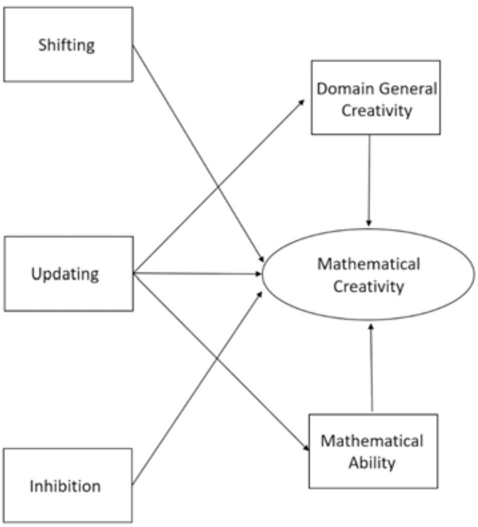

Figure 2. Theoretical model in which updating directly influences mathematical ability and domain-general creativity in addition to all dependent variables having a direct influence on mathematical creativity.

Note. To increase clarity, this image does not show error-terms or that we correlated the errors of the executive functions to account for their overlap.

To investigate these hypotheses, we compared two models. The first model tested if all dependent variables (i.e., shifting, updating, inhibition, domain-general creativity, and mathematical ability) were directly related to mathematical creativity. The second model tested whether updating also had an indirect effect on mathematical creativity through its influence on mathematical ability and domain-general creativity, given that all previous studies consistently report that updating plays the biggest (and most stable) role of all executive functions in creativity and mathematics (e.g., Benedek et al., 2014; Diamond, 2013; Friso-Van den Bos et al., 2013; Van der Ven et al., 2012).

Methods

Data was collected through a large-scale cross-sectional study with one measurement time point with children between the ages of 8 and 13. This study investigated the role of mathematical ability, domain-general creativity, and executive functions during mathematical creativity.

Participants

In the current study, 360 children participated. After excluding any cases with missing data, the final sample was composed of 278 children (M_{age} = 9.71, SD_{age} = 0.93), of which 139 (50.0%) were boys. Based on the minimum requirement of 10 cases per variable for structural equation modelling and 14 observed variables in our model, the sample was deemed sufficient for the intendent statistical method (Kline, 2010). According to a teacher-questionnaire, 7 (2.5%) children that participated had autism or a related disorder and 16 (5.75%) children had an attentional disorder such as ADHD. In the Netherlands, prevalence of autism in 4–12-year olds is around 2.8% (CBS, 2015). According to the DSM-5, the prevalence of ADHD is 5% in children (American Psychiatric Association, 2013). Therefore, we assumed the participants to be a realistic representation of children in Dutch primary school education. Participants were recruited from 21 classes of 9 regular primary schools, situated in the Netherlands. All schools were located in the central part of the Netherlands. Four schools were situated in an urban area (i.e., city with more than 50,000 inhabitants) and five schools were situated in more rural areas. Six of the schools had classes with 20 children or more, whereas the others worked with a system of smaller classes. Children were included in the study if at least one of the parents gave active informed consent. Prior to data collection, the study had been approved by the Ethics Committee of the Faculty of Social and Behavioral Science of Utrecht University in 2016 (FERB16-112).

Procedure

Over the course of two days, participating primary school children were administered a test battery containing several tasks that measured mathematical ability, creativity, executive functioning, and intelligence. On both days, the session was roughly one hour. Testing commenced at the participating primary schools. Children were, therefore, in a familiar and safe environment. Most classes completed the tests on two consecutive days. If this was not possible, the two test days were, at most, nine days apart. On day one, participants completed individual paper-and-pencil tasks in their own classroom. During day one, the participants sat in a test setup and completed the domain-general creativity task amongst several other tasks not relevant to the current study. On day two, participants made one more paper-and-pencil task in the classroom. This task measured mathematical creativity. In addition, the executive functioning tasks were administered individually in a separate quiet room in small groups of maximal six children. There were three executive functioning tasks, two to measure updating and one that measured shifting and inhibition. All executive function tasks were computerized in order to measure reaction time and accuracy. All tests were administered and supervised by at least one test leader. Test leaders were trained prior to data collection by their supervisor and used a protocol during data collection to ensure standard test instructions across classes, schools, and test leaders.

Materials

Inhibition. The Fish Game (Stolte et al., 2019) measured inhibition, which is an adapted version of the classical Flanker task, where the middle target has to be identified amongst distractors. In the Fish Game (of which Figure 3 shows a visual representation), the middle target is flanked by four identical targets that can be identical to the middle target (i.e., congruent trials) or be the mirror image of the middle target (i.e., incongruent trials). The Fish Game also contained so called neutral trials, in which only one stimulus was presented without distractors. The task started with five practice trials, in which the participant received feedback on the accuracy of the responses. The practice trials were followed with a testing block that contained 12 congruent trials, 12 incongruent trials, and 12 neutral trials. Stimulus presentation was at random and participants had 2000 ms to respond. Stimuli were presented either at the top or the bottom of the screen. To measure inhibition, average reaction time during incongruent trials was used. Therefore, this task is a reversed indicator of inhibition. The inhibition block of the Fish Game has good internal consistency as assessed in the current study (neutral trials $\alpha = 0.84$; congruent $\alpha = 0.87$; incongruent $\alpha = 0.88$).

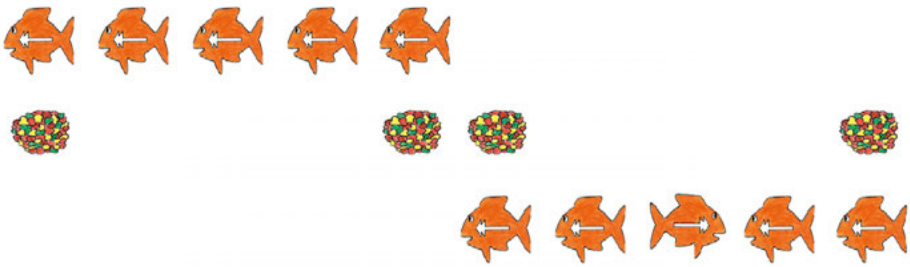

Figure 3. (a) An example of a congruent trial during the Fish Game and (b) an example of an incongruent trial during the Fish Game.

Shifting. The second block of the Fish Game measured the executive function shifting. During this part of the task, the child has to keep shifting between two strategies. The child is instructed that when they see an image of a plant (see Figure 4 for an example), they need to respond to the direction that the fish on the outside are swimming in. This is because the fish on the outside are tired and want to go to sleep between the plants. However, when an image of fish food is presented, the child is instructed to respond to the middle target, as they are used to from the first block of the Fish Game that measured inhibition. The story behind this is that the middle fish is still hungry and, therefore, wants to go to the fish food. This block of the game contains 22 shift trials (the trials with an image of a plant) and 18 non-shift trials (the trials with an image of fish food). Participants had 2500 ms to respond to each trial and trials were presented in a fixed order. The shifting block of the Fish Game has good internal consistency as assessed in the current study (shifting trials' Cronbach's $\alpha = 0.94$; non-shift trials' Cronbach's $\alpha = 0.99$). We measured shifting ability by recording the average reaction time in milliseconds on the shift trials. Therefore, this variable is a reversed indicator of shifting.

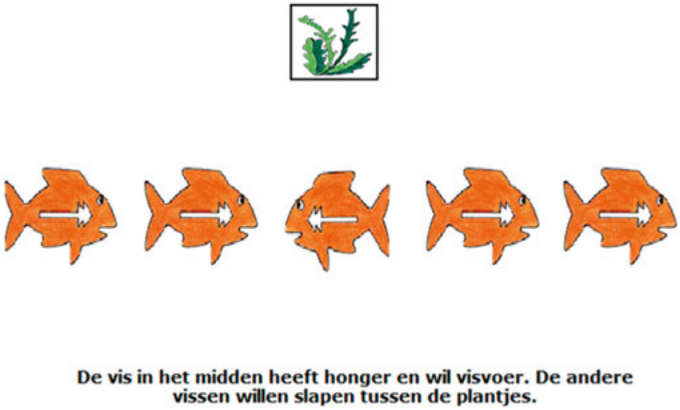

Figure 4. An example of a shifting trial during the Fish Game. Translation of text in the figure: "The fish in the middle is still hungry and wants fish food. The other fishes want to go to sleep between the plants."

Updating. Two tasks were administered to measure updating (Van de Weijer-Bergsma, Kroesbergen, Jolani, & Van Luit, 2016). Verbal updating was measured with the Monkey Game. In this task, the child is instructed to remember and recall a sequence of words in the reversed order. During the task, the child will hear a sequence of spoken words, for example "fire, coat, cat." Then, the child is instructed to remember this sequence in reverse, which, in this case would be "cat, coat, fire." The Monkey Game measures this by letting the child click on the correct words in the correct order. All words are presented in a 3 × 3 matrix. The task contains five levels with four trials. In the first level, the child has to remember and reverse two words. In the last level, the child has to remember and reverse a sequence of five words. Internal consistency of the Monkey Game was found to be "acceptable" to "good" (Cronbach's α between 0.78 and 0.89). Additionally, concurrent validity was also good (ρ between 0.51 and 0.59) (Van de Weijer-Bergsma, Kroesbergen, & Van Luit 2015).

To measure visuo-spatial updating, participants completed the Lion Game (Van de Weijer-Bergsma et al., 2015b). The children were asked to remember where they saw the last lion with a specific color. The task consisted of a 4 × 4 matrix. Every square contained a bush, behind which a colored lion could appear. Each trial, eight lions were presented on the screen, one after the other. Every lion was visible for 2000 ms. Lions could be green, yellow, purple, blue, or red. After eight lions were presented, the child was instructed to click in the matrix where they had seen the last lion with a specific color. The task consisted of 20 trials which were equally divided over five levels. The task increases in difficulty because the number of colored lions that should be remembered increased with every level, starting at two colors and ending with all five colors. The Lion Game has good internal consistency (Cronbach's α between

0.86 and 0.90), good concurrent and predictive validity, and a satisfactory test-retest reliability (ρ = 0.71) (Van de Weijer-Bergsma, Kroesbergen, Prast, & Van Luit, 2015).

For both the Monkey and the Lion Game, the proportion of items correct is recorded, which leads to a score between 0 and 1. The current study created a composite score of updating by first standardizing the outcomes for the Monkey and the Lion Game to account for possible differences in mean and standard deviation between the tasks. Hereafter, the standardized scores were added and subsequently averaged to create the new updating variable.

Mathematical creativity. We measured mathematical creativity with an adapted version of the Mathematical Creativity Test developed by Kattou et al. (2013) (see Schoevers et al., 2018). This task contained five open-ended mathematical questions about geometry that could be answered in multiple ways. Participants are instructed to think of as many answers to each of the mathematical questions as they can. In our adapted and translated version, we aimed to measure the construct of mathematical creativity instead of geometric creativity. To achieve this, we used three questions from the original task and included a similar question that Hershkovitz, Peled, and Littler (2009) used in their research. This question is about dividing a square pie in such a way that four people would get the same amount. This task had the following instruction: "Four children [names given] have to share a square cake fairly. How will they cut the cake?" In addition to this instruction, we included a sentence instructing participants to think of as many different solutions to cutting the cake as they could. Answers were scored on fluency, flexibility (maximum score = 22), and originality (maximum score = 1 for each question). Similar to Leikin and Lev (2013), fluency was operationalized as the sum score of correct answers. Flexibility was operationalized as the number of categories the correct answers could be placed in. Originality was scored by comparing the answer of a participant to a reference group. Previous research reported that the Mathematical Creativity Test had an acceptable internal consistency (Cronbach's α = 78) (Kattou et al., 2013). An exploratory factor analysis was done to investigate if these questions measured the same latent construct.

Mathematical ability. The Cito test is a Dutch ability test used by most Dutch primary schools in grade 1 through 5 to monitor spelling, vocabulary, reading comprehension, and mathematical development (Janssen, Scheltens, & Kraemer, 2007). The test contains multiple choice questions and is used to advise children on the most appropriate level of higher education after primary school and is administered twice a year by teachers. We requested the most recent ability scores of the mathematical part of the Cito test from the participating schools to obtain a measure of participants' standard mathematical abilities. The mathematical part of the Cito has different subtests to measure different types of mathematical ability (e.g., arithmetic, measuring, fractions, percentages, and proportions), adjusted for the level of mathematical ability in each grade. The sum of the subtests leads to a final ability score in a domain, in this case, mathematical ability. The ability scores of the Cito test have a good reliability (Cronbach's α between 0.91 and 0.94 for grades 3 and 5; Janssen, Verhelst, Engelen, & Scheltens, 2010). Since the ability scores differ between grades and schools, in different versions of the Cito test, we made standard scores of all values to be able to compare them.

Domain-general creativity. The Test for Creativity Thinking Drawing Production (TCT-DP) is a measure of general creativity (Kālis, Roķe, & Krūmiņa, 2014; Urban, 2004). We selected this measure as our variable for domain-general creativity since it supersedes the dichotomy of convergent and divergent creativity and incorporates non-cognitive aspects of creativity into the task (Urban, 2004). During administration of the TCT-DP, each participant receives a piece of paper that contains six figural fragments. A test leader than instructs participants that a painter started with this painting and that the participant will now have to finish it however they see fit. Participants have to try to finish the drawing in 15 min (or less). The end product is scored on 14 creativity aspects such as new elements and humor. Time is taken into account if the score of the first 13 creativity aspects is at or above 25 points and a maximum score is calculated. The points gained on the 14 aspects are summed to a total score, which can reach a maximum of 72 points. The TCT-DP has a high differential reliability ($\chi^2 = 33.45$, $C_{(corr.)} = 0.92$) (Urban, 2004) and good interrater reliability in the current study (Cronbach's α = 0.96).

Analyses. The relationship between variables were examined by performing Spearman correlations, as all the variables were found to have a non-normal distribution (based on the Shapiro-Wilks test of normality). Before performing the path analyses, an exploratory factor analysis (EFA) for mathematical creativity was conducted in order to test if one latent construct could be created. Hereafter, path analyses were performed to test our theoretical models. This was done twice; with and without the proposed mediation effects (Figure 1 and Figure 2). In order to formally test our mediation model, we performed a bootstrap with 100 samples. Robust Maximum Likelihood was used to assess the model since our data failed to meet the assumption of normally distributed data. The degree of fit was based on the Chi-square (χ^2) and degrees of freedom (*df*) ratio, the comparative fit index (CFI), the Tucker Lewis index (TLI), and the root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR). The model fit was considered to be good when CFI ≥ 0.95, TLI ≥ 0.95, and RMSEA ≤ 0.06, SRMR ≤ 0.08 and $\chi^2/df < 3$ (Schreiber, Stage, King, Nora, & Barlow, 2006). The analyses were carried out with the sample as a whole, leaving age and gender out of the equation to reduce complexity and in order to have a sufficient sample size for structural equation modelling. The statistical programs, SPSS 24 and the SPSS add-on for structural equation modelling AMOS 24, were used. The Supplementary Materials contains the data package of the current study.

Results

Before testing our hypothesized models, we investigated the correlations between the variables alongside the descriptive statistics, which can be viewed in Table 1, and employed EFA to extract a latent factor of mathematical creativity.

Table 1 *Descriptive statistics and Spearman correlations of the studied variables.*

	Mean	SD	Skew	Kurtosis	1	2	3	4	5	6
1. D-G Creativity	20.33	9.58	0.63	−0.44	-					
2. Math Ability	0.01	1.00	−1.20	4.78	−0.003	-				
3. Updating	0.04	0.83	−0.75	0.73	0.209 ***	0.153 *	-			
4. Shifting	1386.83	236.50	−0.48	0.77	0.072	0.097	0.124 *	-		
5. Inhibition	790.08	151.84	1.12	1.65	0.101	−0.038	0.354 ***	0.416 ***	-	
6. MC (Factor)	0.000	0.69	0.33	−0.23	0.198 **	0.202 **	0.429 ***	0.169 **	0.281 ***	-

Note. D-G = Domain-General; Math Ability = Mathematical Ability; MC = Mathematical Creativity. For shifting and inhibition, scores were reversed so that higher values indicated faster reaction times. *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$.

Mathematical creativity showed significant positive correlations with domain-general creativity, mathematical ability, updating, shifting and inhibition. Moreover, in line with our expectations, domain-general creativity and mathematical ability also had positive correlations with updating.

EFA was performed to investigate if the four questions from the mathematical creativity task measured the constructs of fluency, flexibility, and originality in a similar way. We chose this method because there is no data available on how the three questions from the original mathematical creativity task are related to the question from Hershkovitz et al. (2009) that we included. The results showed that when all four questions were added to the analyses, there was no significant increase in the amount of explained variance (73.16% versus 74.07%) compared to when the three original questions from Kattou et al. (2013) were added. In addition, in the EFA containing three factors, all correlations between the scoring components (i.e., fluency, flexibility, and originality) were significant, whereas this was not the case when all four questions were included. Therefore, we concluded it was best to exclude question number 2 from Hershkovitz et al. (2009) from further analyses. In other words, it seems that the three separate questions from the mathematical creativity task each measure a unique part of mathematical creativity. In question 1, for example, creative geometry is examined; question 3 is about creating an equation, and question 4 is about number sense.

As for the two different models tested, Model 1 (the starting model, with 57 estimated parameters, depicted in Figure 1) showed a good fit to the empirical data (CFI = 0.972, TLI = 0.958, χ^2 = 97.32, df = 62, χ^2/df = 1.57, p = 0.003, RMSEA = 0.045 (90% CI: 0.027–0.062), SRMR = 0.059). A full representation of the model can be viewed in Figure 5. The starting model demonstrated a positive relation between shifting, updating, inhibition, domain-general creativity, mathematical ability and mathematical creativity. Unlike the significant Spearman correlations, the effects of inhibition (Standard Error = 0.000; Critical Ratio = −1.563; p = 0.118), shifting (Standard Error = 0.000; Critical Ratio = −0.862; p = 0.389), domain-general creativity (Standard Error = 0.012; Critical Ratio = 1.875; p = 0.061), and mathematical ability (Standard Error = 0.061; Critical Ratio = 1.461; p = 0.144) on mathematical creativity were not statistically significant. The effect of updating on mathematical creativity was statistically significant (Standard Error = 0.094; Critical Ratio = 5.314; p < 0.001) (see Figure 5).

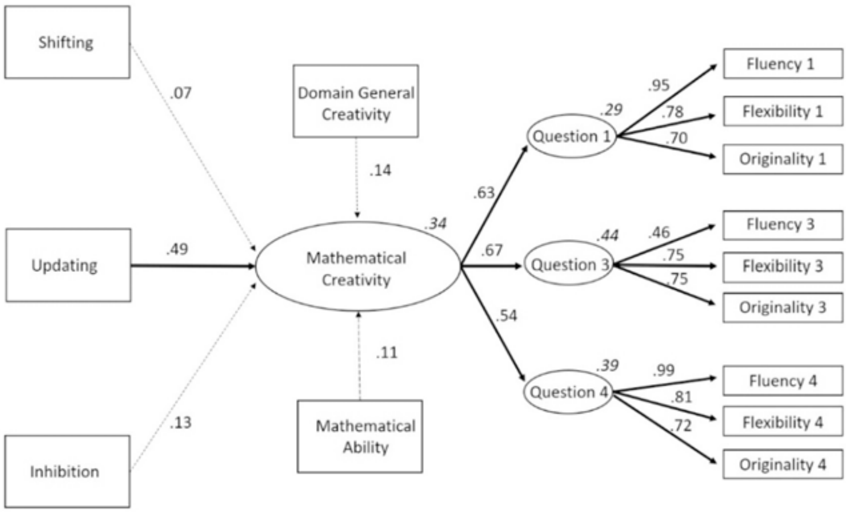

Figure 5. Standardized factor loadings of the starting model, with only direct effects on mathematical creativity (Model 1). Bold arrows signify a significant relation, striped arrows signify an insignificant relation. R^2 of the endogenous variables is added in cursive above its rectangle.

Note. To increase clarity, this image does not show error-terms or that we correlated the errors of the executive functions or the error covariances between fluency, flexibility, and originality to account for their overlap.

Next, we tested Model 2, with direct associations between updating on the one hand and mathematical ability, domain-general creativity and mathematical creativity on the other (as originally depicted in Figure 2). This model had 59 estimated parameters which met the fit requirements (CFI = 0.990, TLI = 0.985, $\chi^2 = 72.64$, df = 60, $\chi^2/df = 1.21$, $p = 0.13$, RMSEA = 0.028 (90% CI: 0.000–0.047), SRMR = 0.043). For a full visual representation of the results, see Figure 6 This model revealed a positive influence of updating on mathematical ability and mathematical creativity. Furthermore, shifting, updating, inhibition, mathematical ability, and domain-general creativity also positively influenced mathematical creativity. The effects of inhibition (Standard Error = 0.000; Critical Ratio = −1.564; $p = 0.118$), shifting (Standard Error = 0.000; Critical Ratio = −0.878; $p = 0.380$), mathematical ability (Standard Error = 0.061; Critical Ratio = 1.476; $p = 0.140$), and domain-general creativity (Standard Error = 0.006; Critical Ratio = 1.887; $p = 0.0.59$) on mathematical creativity were not statistically significant. All other paths were statistically significant (see Figure 6 and Table 2). Thus, although the total mediation effect of updating on mathematical creativity through mathematical ability or domain-general creativity was not significant, we can still conclude partial mediation is present (MacKinnon, Lockwood, Goffman, West, & Sheets, 2002; Shrout & Bolger, 2002; Zhao, Lynch, & Chen, 2010).

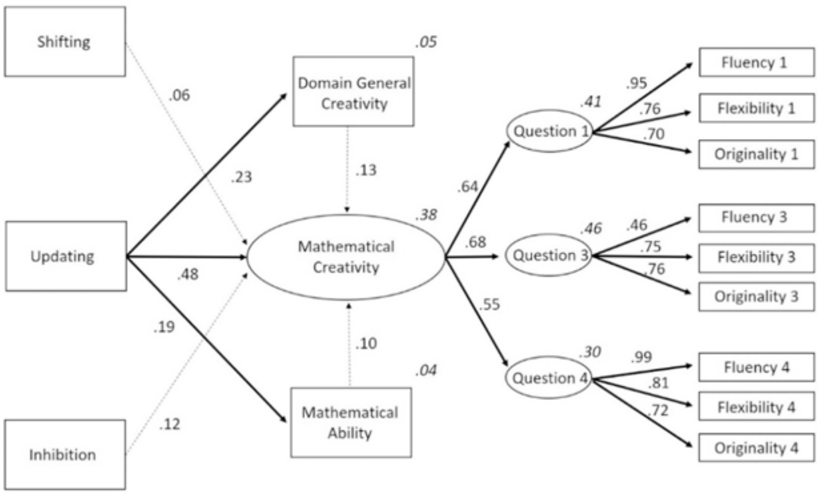

Figure 6. Standardized factor loadings of the second model with indirect and direct effects of updating on mathematical creativity (Model 2). Bold arrows signify a significant relation, striped arrows signify an insignificant relation. R^2 of the endogenous variables is added in cursive above its rectangle.

Note. To increase clarity, this image does not show error-terms or that we correlated the errors of the executive functions or the error covariances between fluency, flexibility, and originality to account for their overlap.

Table 2 *Results of testing the second model with the direct and indirect effect of updating on mathematical creativity (structural and measurement models).*

			Standardized Coefficients	SE	CR	P
Structural Model						
D-G Creativity	→	Updating	0.226	0.672	3.865	***
Math Ability	→	Updating	0.189	0.071	3.212	0.001
Math Creativity	→	Math Ability	0.102	0.061	1.476	0.140
Math Creativity	→	D-G Creativity	0.132	0.006	1.887	0.059
Math Creativity	→	Inhibition	0.121	0.000	−1.564	0.118
Math Creativity	→	Shifting	0.063	0.000	−0.878	0.380
Math Creativity	→	Updating	0.475	0.090	5.521	***
Measurement Model						
Question 1	→	Math Creativity	0.638	-	-	-
Question 3	→	Math Creativity	0.677	0.645	4.767	***
Question 4	→	Math Creativity	0.549	0.165	5.910	***
MC 1 fluency	→	Question 1	0.950	-	-	-
MC 1 flexibility	→	Question 1	0.760	0.030	13.842	***
MC 1 originality	→	Question 1	0.699	0.014	12.603	***
MC 3 fluency	→	Question 3	0.460	-	-	-
MC 3 flexibility	→	Question 3	0.754	0.025	6.428	***
MC 3 originality	→	Question 3	0.755	0.007	6.438	***
MC 4 fluency	→	Question 4	0.987	-	-	-
MC 4 flexibility	→	Question 4	0.809	0.030	17.092	***
MC 4 originality	→	Question 4	0.722	0.009	14.363	***

Note. D-G = Domain-General; Math Ability = Mathematical Ability; MC = Mathematical Creativity Question; Standardized Coefficients = Standardized Regression Weights; SE = Standardized Errors; CR = Critical Ratio; p = Probability; Structural Model = relation between the independent and the dependent variables in the model; Measurement Model = relation between the latent variables and the observed variables in the model.

For shifting and inhibition, scores were reversed so that higher values indicated faster reaction times.

*** $p < 0.001$.

This second model had a lower AIC and BCC (AIC = 19064, BCC = 197.40) compared to the first model (AIC = 211.32, BCC = 217.84), which indicates that it fits the data better. For a complete overview of statistics of the second model, see Table 2.

Table 2 shows the coefficients of the relations in the structural and measurement models of the second model, as well as their corresponding estimation errors, critical ratio, and associated significance. The measurement model represents the relations between latent variables or composite variables while the structural model tests all the hypothetical dependencies based on path analysis (Kline, 2010).

Discussion

The aim of the current study was to provide an overview of the relation between executive functions, domain-general creativity and mathematical ability on mathematical creativity. To this end, we tested and compared two models. The first model consisted of only direct relations of mathematical ability, domain-general creativity, and executive functions (shifting, updating, and inhibition) on mathematical creativity. The second model consisted of all direct relations including indirect effects of updating through its influence on domain-general creativity and mathematical ability. Based on the correlational analyses, we found significant associations between mathematical creativity and updating, shifting, inhibition, mathematical ability, and domain-general creativity. Furthermore, our results revealed that a model in which mathematical ability and domain-general creativity act as partial mediators between updating and mathematical creativity, and where updating also has a direct relation to mathematical creativity, fitted the data best. More specifically, there was a positive relation between updating and mathematical ability, domain-general creativity, and mathematical creativity. Additionally, mathematical creativity was positively related to updating directly as well.

Concerning the relation between updating and mathematical creativity, we found most support for the model in which updating influenced mathematical creativity directly and indirectly through its positive association with mathematical ability and domain-general creativity. Although this has not been studied before in the domain of mathematical creativity or in children, this result was not unexpected because it is in line with the known relation between general creativity and updating in adults (Diamond, 2013; Benedek et al., 2014) and with the relation between mathematical ability and updating in children (e.g., Friso-Van den Bos et al., 2013; Van der Ven et al., 2012). Thus, since mathematical creativity requires both domain-general creativity and mathematical ability, it can be argued that updating exerts its influence on mathematical creativity in direct and indirect ways. That is, although the total effect of the mediator on mathematical creativity was not significant, indirect mediation was still present since the path between updating and domain-general creativity, and updating and mathematical ability was significant (MacKinnon et al., 2002; Shrout & Bolger 2002; Zhao et al., 2010). Updating plays a vital role in both processes because it allows for the storage of intermediate results or ideas. Mathematical tasks and creativity tasks are often comprised of a multi-step process in which updating is therefore necessary to move from one step to the next. To apply one's abilities creatively, preexisting knowledge and skills should be activated, and working memory continuously updated to come to creative solutions (Benedek et al., 2014).

Similarly, general creative abilities are transferable to specific domains and therefore, requested during mathematical creativity, too (Jeon et al., 2011). Thus, well developed general creative abilities might make it possible to use one's mathematical abilities creatively during a divergent thinking task (Bahar & Maker, 2011; Sak & Maker, 2006). However, it is not possible to make a prediction about the direction of this relation at this point and it may be that mathematical ability influences domain-general creativity, too (Kattou et al., 2013). Furthermore, one can question whether our current task to assess mathematical creativity did indeed measure this construct or if the strong connection between executive functions and mathematical creativity reflect the predicted positive link between novelty and executive function as well (Davidson et al., 2006; Rhoades et al., 2011; Van der Sluis et al., 2007). In a regular classroom environment, mathematics and divergent thinking are seldom combined. Therefore, the mathematical creativity task that we used may have made an appeal to the executive functions of the participating children because of their unfamiliarity with such tasks and because of the divergent thinking aspect, which explains the strength of the correlation that we found. Additionally, since the positive correlation between mathematical abilities and mathematical creativity was no longer significant after executive functions were taken into account, there appears to be a common variance between the two. We recommend future studies to take other (domain-general) cognitive factors into account, such as intelligence, processing speed, or motivational factors (Brydges et al., 2012; Clark, Nelson, Garza, Sheffield, & Espy, 2014; Duan et al., 2010; Tella, 2007; Moenikia & Zahed-Babelan, 2010).

Although this study replicated the positive relation between updating, domain-general and domain-specific aspects of creativity, the role of response inhibition and shifting on creativity and mathematics is still debatable. Regarding inhibition, we found a significant relation between inhibition and mathematical creativity in the correlational analysis but in the path model there was no such effect. This may be because there is overlap of response inhibition with updating and shifting (Miyake et al., 2000). Therefore, the explained variance of inhibition may have gone through the other two executive functions instead. Since the executive functions are still developing in our included age range, it is possible that the three functions are not fully distinct factors yet (Huizinga, Dolan, & Van der Molen, 2006; Van der Sluis et al., 2007; Van der Ven et al., 2012). Since making different age groups within the current sample would have led to too small samples to draw definite conclusions, we recommend future research to be done with a larger sample size to replicate and expand the current results with more specific information about the contribution of age and gender to the model.

In the correlational analysis, the current study found that response inhibition had a small positive, albeit nonsignificant, predictive value on domain-general creativity but a significant positive relation to mathematical creativity. This deviates from previous results that investigated domain-general creativity (Benedek et al., 2014; Cassotti et al., 2016; Edl et al., 2014). This suggests that the relation between inhibition and creative activities may be task dependent, and something similar may have played a role in our other variables of interest as well. This is further corroborated in the study by White and Shah (2006). This provides support that inhibition can either help or harm the creative process, depending on the specific measure of creativity. Previous literature indicated that creativity and good response inhibition were connected by the suppression of interferences from dominant responses (e.g., Benedek, Franz, Heene, & Neubauer, 2012; Groborz & Necka, 2003) but negative correlations were found when no such interference was present (Vartanian, Martindale, & Kwiatkowski, 2007). For instance, the TCT-DP may require less response inhibition because of a lack of interference during the task. When this task is first presented, divergent thinking is important to stipulate the different options of finishing the painting, and response inhibition is necessary to delay making a decision what to draw until you have reviewed several ideas. After assessing all options, convergence is necessary to choose which option to draw, which requires good response inhibition (White & Shah 2006). However, since the TCT-DP is not a particularly time sensitive or complex task, with no 'incorrect' answers, the executive functions are probably less engaged (Miyake et al., 2000). Since no competing concepts or ideas are present anymore at the stage of drawing, response inhibition is probably less important.

However, in a divergent task such as our mathematical creativity task, it seems plausible that some response inhibition is needed to overcome interference of common ideas. To generate more creative ideas, it is necessary to activate concepts that are more distantly associated with a task or problem, which is related to earlier forms of inhibition and attention (Benedek, Könen, & Neubauer, 2012; Carson et al., 2003; Friedman & Miyake, 2004). When stated this way, perhaps it is not so much efficient response inhibition that is important during mathematical creativity but efficient updating skills. At first, the most common and closely related concepts are activated in working memory. Hereafter, updating is required to facilitate the process of gating less obvious information into working memory as well (Benedek et al., 2014; Diamond, 2013). These strong and weakly related concepts can be combined to form novel and creative ideas (Mednick, 1962). As such, it is not necessarily the inhibition of irrelevant information that is important but the continuous updating of the information in the working memory, in order to create new combinations, that is important for creativity.

Regarding the relation between shifting and mathematical creativity, the current study found no support that well developed shifting abilities are linked to mathematical creativity once the overlap with updating was accounted for. Shifting, as well as other executive functions, are used during perspective taking. That is, processes such as perspective taking first require inhibition of the old perspective, making space for new ideas (i.e., the process of updating working memory) to come to a new perspective or idea (Davidson et al., 2006). Therefore, it is often cited that (cognitive) flexibility or shifting are paramount in creativity and mathematics (Bailey, McDaniel, & Thomas, 2007; Bull & Scerif, 2001; Nijstad et al., 2010; Yeniad et al., 2013). Within the field of mathematics, there is research supporting this finding (i.e., Clark, Pritchard, & Woodard, 2010; Mayes, Calhoun, Bixler, & Zimmerman, 2009) although not all studies find such clear results when other executive functions are added (Espy et al., 2004; Toll et al., 2011). However, for the field of mathematical creativity, such empirical evidence is missing. One study on shifting and creativity did find a relation between creativity and shifting (Pan &Yu 2018) but the only other study that investigated this relation did not (Benedek et al., 2014). Providing an explanation for this difference in results is difficult. Perhaps the difference in age of participants, the complexity of the task, or the type of creativity task (domain-general versus mathematical creativity) was a factor or the difference in the measurement of shifting (difference score or reaction time of shift-trials). More likely, however, the difference in whether or not shared variance with updating was taken into account explains these discrepancies in results (Van der Ven et al., 2012). The current study further strengthens the idea that shifting and inhibition are ancillary to updating during creative and mathematical tasks.

Conclusions and future directions

The current study provided the first theoretical model that included the roles of the executive functions of updating, shifting and inhibition, mathematical ability, and domain-general creativity, on mathematical creativity in children. This contributed to our understanding of the complex underlying factors to mathematical creativity and further strengthens the idea that creativity/divergent thinking is a top-down process (Razumnikova, 2007; Zabelina, Colzato, Beeman, & Hommel, 2016). The substantive sample size allowed for employing structural equation modelling which made it possible to test the fit of several models to the data and to compare these models against each other. In addition, from a theoretical perspective, the graphical representation of the relations between variables increases our understanding of set connections and it provides a means to examine the impact of direct as well as indirect relations within the same analysis.

Our study implies that updating is associated with mathematical creative performance in a direct and in a smaller capacity, as well as in an indirect manner because it positively predicted domain-general creativity and mathematical ability as well. Although the current study contributed to our understanding of mathematical creativity, it is not without its limitations. First, caution should be taken when generalizing these results as it seems that results are task dependent. In the current study, we used a mathematical divergent thinking task, while convergent thinking was not measured separately. Therefore, conclusions are limited to divergence. Future research should take both forms of creativity into account to provide a more complete picture. Second, it is recommended to use more than one measure for domain-general creativity in the future to better capture the entire construct of general creative abilities (Cropley, 2010). Although the TCT-DP is widely used to measure creativity thinking and creative potential in a culturally independent way, domain-specific abilities are involved (Kālis et al., 2014; Urban, 2004). Third, since the current study had one measurement time point, it is not possible to say something about the causal relationships between variables. Therefore, it would be beneficial to carry out future research with a longitudinal design to examine if the implied causal relations described here can be confirmed. Additionally, our sample was restricted in terms of age. This makes any generalization of our results to other age groups difficult, especially since the ability of inhibiting one's irrelevant thoughts and responses is still developing until the age of 11, shifting abilities until the age of 12, and updating, even until 18 years of age (Carlson, Mandell, & Williams, 2004; Gathercole, Pickering, Ambridge, & Wearing, 2004; Huizinga et al., 2006; Huizinga & Van der Molen, 2007).

Despite these limitations the current study provided a first look at the underlying cognitive factors of mathematical creativity in primary school children. These results can have important implications for how primary school teachers can promote (mathematical) creativity. While the effectiveness of training programs for executive functions is up for discussion (Karbach & Unger 2014), insight into a person's strengths and weaknesses can serve an important purpose for psychoeducation, for example. By creating awareness about the role of, and perhaps providing training in executive functions such as updating abilities, creativity can be promoted in domain-general and domain-specific ways.

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Prepulse inhibition and P50 suppression in relation to creativity and attention: Dispersed attention beneficial to quantitative but not qualitative measures of divergent thinking

This chapter is under review as: Stolte, M., Oranje, B., & Van Luit, J. E. H, & Kroesbergen, E. H. Prepulse inhibition and P50 suppression in relation to creativity and attention: Dispersed attention beneficial to quantitative but not qualitative measures of divergent thinking.

Author contributions: E.H.K., B.O., J.E.H.V.L., and M.S. conceptualized the research; M.S. collected the data; M.S., and B.O. processed and analyzed the data, M.S. wrote the original draft and edited the paper; E.H.K., J.E.H.V.L., and B.O. critically reviewed the pape

Abstract

The current study investigated whether lower sensory and sensorimotor gating were related to higher levels of creativity and/or attentional difficulties in healthy 9- to 13-year-old children. Psychophysiological gating was measured with P50 suppression and prepulse inhibition of the startle reflex (PPI). The final sample included 65 participants in the P50 analyses and 37 participants in the PPI analyses. Our results showed that children with a high P50 amplitude to the testing amplitude scored significantly higher on the divergent outcome measures of fluency and flexibility but not originality compared to children with a lower amplitude. No significant differences in attention were found between children with low or high sensory or sensorimotor gating. The data suggest that quantitative, but not qualitative measures of divergent thinking benefit from lower psychophysiological gating and that attentional difficulties stem from specific instead of general gating deficits. Future studies should take the effect of controlled attention into consideration.

Keywords: Creativity; Sensory gating; Sensorimotor gating; EEG; Psychophysiological gating; Attention

Introduction

There appear to be two sides to decreased sensory gating, the neurophysiological measure of inhibition responsible for filtering incoming stimuli to reduce strain on higher brain functions (Jones, Hills, Dick, Jones, & Bright, 2016). On the one hand, it may cause more distractibility and errors (Ansburg & Hill, 2003; Aron, Downson, Sahakian, & Robbins, 2003). On the other hand, a broader attentional range can be beneficial during a situation in which there are several courses of action or during creative acts (Carson, Peterson, & Higgins, 2003; Gonzalez-Carpio, Serrano, & Nieto, 2017; Zabelina, O'Leary, Pornpattananangkul, Nusslock, & Beeman, 2015). Creativity can be defined as the interaction between process, ability, and environment to create something meaningful and original based on contextual factors (Brandau et al., 2007; Plucker, Beghetto, & Dow, 2004). Since awareness of promoting creativity in primary school curricula is increasing (Craft, 2003; Pang & Plucker, 2012) and creativity has been linked to attentional difficulties (Paek, Abdulla, & Cramond, 2016), the current paper investigated sensory and sensorimotor gating in relation to creativity and attention.

Two paradigms commonly believed to measure inhibiting irrelevant or distracting information are sensorimotor gating (prepulse inhibition; PPI) and sensory gating (P50 suppression). During PPI, a muted or inhibited magnitude of the startle reflex is found when an intense, startle eliciting stimulus is presented after a weak stimulus (the prepulse). In humans, this is usually assessed with electromyography (EMG) of the orbicularis oculi muscle (Gebhardt, Schulz-Juergensen, & Eggert, 2012; Madsen, Bilenberg, Cantio, & Oranje, 2014; Richards, 1998).

Similar to PPI, P50 suppression represents the influence of inhibitory processes triggered by earlier presented stimuli. In a typical P50 paradigm, participants are presented with pairs of identical auditory stimuli with an ISI of 500 ms (Hammer et al., 2007; Zabelina et al., 2015). In healthy participants, the event related potential (ERP) to the second stimulus is usually reduced, starting from the positivity emerging in the electroencephalogram (EEG) after 50 ms (P50) onwards (Davies, Chang, & Gavin, 2009; Madsen et al., 2015; Oranje, Geyer, Bocker, Kenemans, & Verbaten, 2006). This decrease in P50 amplitude is thought to reflect sensory gating.

Some studies report that P50 suppression and attentional measures are correlated (Bak, Glenthøj, Rostrup, Larsson, & Oranje, 2011; Lijffijt et al., 2009; Wan, Friedman, Boutros, & Crawford, 2008), but studies showing that attention and P50 suppression are unrelated also exist (Jerger, Biggins, & Fein, 1992; Kho et al., 2003). This difference is likely due to the differences in attentional measures that were assessed in these studies. In children (age 9-14), symptomatology of the attentional disorder ADHD has been negatively associated with levels of P50 suppression, as well as its peak amplitude, and peak latency (Durukan et al., 2016). Likewise, a study with adults reported that patients with ADHD had lower average P50 suppression compared to controls (Holstein et al., 2013). However, others report that P50 deficits are not related to ADHD or schizophrenia (Lemvigh et al., 2020; Olincy et al., 2000). Furthermore, ADHD has also been associated with reduced PPI in children (Ornitz et al., 1999). Yet, results are scarce and do not show a definite relation since replication of this result in adults or adolescents was unsuccessful (Feifel, Minassian, & Perry, 2009; Holstein et al., 2013; Rydkjaer et al., 2020).

To date, only one EEG-study exists in which the association between sensory gating and creativity was investigated in 84 healthy adults. The authors reported that divergent thinking was related to increased sensory gating and that real-life creative achievements were related to reduced sensory gating (Zabelina et al., 2015). They reasoned that divergent thinking depends on the ability to rapidly focus attention by restraining sensory gating. However, results may be different when there are no severe time constraints. Because reduced gating theoretically leads to a wider range of stimuli in working memory to combine, this in turn might increase original and creative ideations to evolve (Stolte, Kroesbergen, & Van Luit, 2019; Thompson-Schill, Ramscar, & Chrysikou, 2009). Therefore, we hypothesized that higher values of creativity or attentional difficulties would be related to increased psychophysiological responses to irrelevant stimuli, and thus lesser PPI and P50 suppression.

Method

All tests were performed at the Utrecht Medical Centre and approved by the Faculty Ethics Review Board (FETC18-081) and Medical Ethical Committee of the Utrecht Medical Centre (NWMO18-849).

Participants

Participants were invited from a behavioural study that investigated the relation between creativity, executive functioning, and mathematics in primary school children (*N* = 360) (Stolte, García, Van Luit, Oranje, & Kroesbergen, 2020). In total, 70 of these invited 360 children were found willing to participate in the current EEG-study. Three children were excluded based on a suspicion or diagnosis of an autism spectrum disorder, as indicated by the parents. One participant showed no identifiable P50 waveform, 30 participants did not show PPI above noise level or were unable to finish the task due to discomfort caused by the sheer intensity of the stimuli, and data from one participant was lost due to technical issues. Additionally, missing data was present for one participant on the Test for Creative Thinking-Drawing Production (Urban, 2004), for two participants on the mathematical creativity test, and three participants on the attentional questionnaire. Hence, 65 participants (36 boys) were included in the analyses of the P50 paradigm (Mean age = 10.77; *SD* = .84; Range = 9.30 – 12.72) and 37 participants (23 boys) were included in the analyses of the PPI paradigm (Mean age = 10.79; *SD* = .70; Range = 9.30 – 12.40).

Procedure

Before testing, we obtained active informed consent from at least one parent. The Copenhagen Psychophysiological Testbattery (Oranje, Wienberg, & Glenthøj, 2011; Oranje, Jensen, Wienberg, & Glenthøj 2008) was assessed in a dimly lit, soundproof room; the battery took approximately 70 minutes to complete. Beforehand, a screening for possible hearing deficits was performed. Participants were instructed to sit upright but relaxed. Given the specific topic of this paper, we only focussed on the results of the sensory- and sensorimotor gating tasks, the other results will be published elsewhere.

Behavioral instruments

Test for Creative Thinking-Drawing Production (TCT-DP). To test creativity, participants completed the TCT-DP. Participants had 15 minutes to complete a drawing containing six figural fragments. Fourteen creativity aspects were scored to create a total score. The interrater reliability was found to be good (*r* = .87) and the differential reliability is high (χ^2 = 33.45, $C_{(corr.)}$ = .92; Urban, 2004).

Mathematical creativity test. In order to test different subcomponents of divergent creativity, we administered a mathematical multiple solution test containing four questions. One question was to name multiple ways to equally divide a cake for four people (Hershkovitz et al., 2009). The other three questions were about identifying reasons why a shape did not belong to a group of shapes, why a number did not belong, and thinking of multiple ways how a calculation can start with “7” and have the answers “21” (Kattou et al., 2013; Schoevers et al., 2020). All questions were scored on originality (the novelty of an answer), flexibility (the different strategies or categories answers belong to), and fluency (the number of correct answers provided). The internal consistency of the task was acceptable (Cronbach’s α = .78; Kattou et al., 2013).

Strength and Difficulties Questionnaire (SDQ). Attentional difficulties were assessed with the SDQ, a comprehensive questionnaire filled in by parents (Goodman, 2001). The SDQ had 25 questions with a 3-point Likert scale and was comprised of five scales. The reported internal consistency of the hyperactivity/inattention subscale is satisfactory (Cronbach’s α between .65 and .88) and concurrent validity is acceptable (Goodman, 2001; Mieloo et al., 2013).

Intelligence. The subtest ‘results’ from the NIO (Dutch intelligence test for educational level; Nederlandse Intelligentietest voor Onderwijsniveau) was used. During this task, participants had to indicate which of five two-dimensional shapes can be folded into a three-dimensional shape. For each assignment, a total of five points could be scored and a sumscore was created. Internal consistency for the subtest ‘results’ was good (Cronbach’s α = .82; Van Dijk & Tellegen, 2004).

Paradigms

PPI and habituation paradigm. This paradigm took 27 minutes and started with the presentation of 5 minutes of white, background noise of 70 dB to acclimate the participant. Hereafter, during Block 1 and 3, a series of eight pulse-alone (PA) trials were presented with white noise burst of 116 dB lasting 20 ms to measure habituation. The intertrial intervals were randomized between 10 and 20 seconds. Block 2 contained PA and prepulse-pulse trials to measure PPI. Prepulses consisted of white noise bursts of either 76 or 85 dB lasting 20 ms. Intertrial intervals were randomized between 10 and 20 seconds. The stimulus onset asynchrony between the prepulse and pulse stimuli was either 60 or 120 ms. Each prepulse-pulse combination was presented 10 times.

P50 paradigm. To measure the P50 ERP, a standard P50 paradigm was used. Auditory stimuli were paired, short bursts of white noise of 90 dB and a duration of 1.4 ms, with an 10 seconds ISI and 500 ms intrapair interval. Stimuli were presented in three blocks of 40 click-pairs to combat drowsiness and boredom. Participants were instructed to count the clicks to avoid drowsiness even further (Bak et al., 2017; Micoulaud-Franchi et al., 2019; Oranje et al., 2011). Each block lasted approximately 7 to 8 minutes.

Data processing

BioSemi® hardware (BioSemi, Netherlands), containing 64 Active Two electrodes arranged according to the 10-20 system (Jaspers, 1958) recorded all electroencephalogram (EEG) and electromyogram (EMG) activity. Sampling was done in a continuous fashion. Signals were digitized at 2 kHz by a computer.

The eye-blink component of the acoustic startle response was measured by recording EMG activity from the right orbicularis oculi, for which purpose two electrodes were placed under the right eye. The first of these was aligned with the pupil, the other was positioned laterally. BESA software (version 6.0, MEGIS Software, Gräfelfing, Germany) was used to process the data.

PPI paradigm. First, data was filtered between 25 and 250 Hz. Hereafter the highest amplitude in the time interval 20 – 140 ms after the startle-eliciting pulse was scored as the startle amplitude. Here, PPI was calculated as ([1-(PP/PA)]*100%); in which PP was the average startle amplitude to prepulse – pulse trials and PA was the average amplitude to pulse alone trials of block 2. Based on the different stimulus onsets (60 or 120 ms) and intensities (76 or 85 dB) this resulted in five outcome measures, including PA.

P50 paradigm. The surrogate model of BESA was used to correct for eye-blinks and -movements. If the difference between minimum and maximum amplitude exceeded 150 µV in the relevant scoring window, epochs were removed as a correction for non-paradigm-related artifacts. Hereafter, all epochs were averaged and subsequently filtered between 1 – 70 Hz. The largest through-to-peak P50 amplitudes were scored from electrode Cz, where the highest amplitude was reached, with average reference in the 35 – 90 ms interval after the first (conditioning, C) stimulus of the paired-click trial (Nagamoto, Adler, Waldo, & Freedman, 1989; Oranje et al., 1999). The P50 amplitude of the second (testing, T) stimulus was defined as the largest through-to-peak amplitude within the latency of the maximum P50 amplitude to the C-stimulus, ± 10 ms. P50 suppression was expressed as the ratio T/C.

Statistical analysis

All data was analysed with IBM SPSS Statistics 24. The distribution of the data was determined with Kolmogorov Smirnov tests. First, the correlations between all variables were checked and possible covariates for age, gender, and intelligence were identified. Second, we grouped participants based on their sensory and sensorimotor gating performance. For each of these outcome variables, two groups were created based on scores above and below the group average. Third, we investigated if these groups differed on creativity and attentional measures. As such, ANCOVAs or Mann Whitney U tests were performed, depending on whether intelligence, age, and gender correlated significantly with the dependent variables or not.

Results

P50 paradigm

Table 1 shows the descriptive statistics of the P50, creativity, and attentional outcome measures and significant correlations with covariates. Based on the significant correlations, we corrected for intelligence on all creativity measures and for gender and age on originality.

Table 1 *Mean, standard error of the P50, creativity, and attentional outcome measures, and significant Spearman correlations to the control variables Intelligence, Age, and Gender.*

	Mean	Standard Error	Correlation to Age, Gender, and Intelligence
Conditioning amplitude	1.55	1.14	Fluency x Intelligence (r_s = .544)**
Testing amplitude	.88	.11	Flexibility x Intelligence (r_s = 409)**
T/C ratio	.72	.11	Originality x Intelligence (r_s = .299)*
Fluency	15.06	.97	Originality x Gender (r_s = .259)*
Flexibility	7.44	.30	Originality x Age (r_s = .261)*
Originality	1.77	.08	TCT-DP x Intelligence (r_s = .441)**
TCT-DP	22.08	1.36	
Attention	3.92	.34	

** $p < .01$; * $p < .05$

Based on our prior hypothesis that the low sensory gating group would have increased creativity scores we performed ANCOVAs to test our predictions. When split on (above and below) average conditioning amplitude we found no significant group effects on any of the creativity scores, i.e. fluency, flexibility, originality and TCT-DP ($F < 2.57$, $p > .114$, $\eta_p^2 < .042$). When split on (above and below) average testing amplitude a significant main effect of group was found on fluency, ($F(1,59) = 6.524$, $p = .013$, $\eta_p^2 = .100$) and flexibility ($F(1,59) = 6.556$, $p = .013$, $\eta_p^2 = .100$), indicating higher creativity scores in the group with higher testing amplitude than in the group with lower amplitudes. However, no significant main group effect was found on originality ($F(1,58) = 2.466$, $p = .122$, $\eta_p^2 = .041$) or TCT-DP ($F(1,60) = .377$, $p = .541$, $\eta_p^2 = .006$). Similar to the split on conditioning amplitude, when split on (above and below) average T/C ratio no significant group effects in the creativity measures were found at all ($F< .787$, $p > .378$, $\eta_p^2 < .013$).

Since the SDQ attention scale did not significantly correlate with any of our covariates, Mann Whitney U tests were performed to test the prediction that the group with low sensory gating would have increased attentional difficulties. These tests showed no significant group differences when groups were split on (above or below) average conditioning amplitude, testing amplitude or T/C ratio ($z < -.817$, $p > .414$).

Correlational analyses between P50 measures and measures of creativity and attention showed only one significant correlation: the conditioning amplitude correlated significantly positive with flexibility ($r_s = .338$, $p = .007$).

PPI paradigm

Table 2 shows descriptive statistics of the PPI creativity, and attentional outcome measures and significant correlations with covariates. We corrected for intelligence on fluency and flexibility, for age on fluency and originality and for gender on all four trial types.

Table 2 *Mean, standard error of the PPI, creativity, and attentional outcome measures, and significant Spearman correlations to the control variables Intelligence, Age, and Gender.*

	Mean	Standard Error	Correlation to Age, Gender, and Intelligence
Pulse alone	47.32	4.31	Fluency x Intelligence (r_s = .528)**
R7660	-44.27	61.20	Flexibility x Intelligence (r_s = 478)**
R76120	30.46	5.47	Fluency x Age (r_s = 328)*
R8560	16.16	7.00	Originality x Age (r_s = .398)*
R85120	37.76	5.17	R7660 x Gender (r_s = -.433)**
Fluency	13.46	1.23	R76120 x Gender (r_s = .-329)*
Flexibility	6.94	.38	R8560 x Gender (r_s = .525)**
Originality	1.70	.10	R85120 x Gender (r_s = .-.371)*
TCT-DP	23.00	1.80	
Attention	4.11	.45	

** $p < .01$; * $p < .05$

When groups were split on above or below average PPI, we only found a significant group difference in TCT-DP score in the PPI R7660 condition ($F(1,33) = 8.918$, $p = .005$, $\eta_p^2 = .213$), indicating higher creativity scores in the group with lower PPI compared to the group with a higher PPI. No significant group differences were found when split on any of the other PPI trial types, including habituation, nor on pulse alone amplitude ($F < 4.028$; $p > .053$, $\eta_p^2 < .109$).

No significant group differences were found in attention when groups were split on any of the PPI trial types or pulse alone amplitude ($F < 3.941$; p > .055, $\eta_p^2 < .104$), and neither did any of the PPI measures correlate significantly with any of the creativity or attentional measures ($r_s < -.238$, $p = .156$).

Discussion

The current study found that children with a higher P50 amplitude in response to the testing stimuli had significantly higher scores on the divergent thinking measures fluency and flexibility. No differences were found on other creativity measures, attentional difficulties, or when the group was differentiated on sensorimotor gating measures except higher creativity scores in the lower sensorimotor gating group for one of the four trial types (R7660).

Contrary to the previous findings in an adult sample (Zabelina et al., 2015), we found that our children with above group average responses to the testing stimuli of the P50 suppression paradigm also scored higher on divergent thinking (however, please note that no significant differences were observed for T/C ratio or conditioning amplitude). Zabelina and colleagues (2015) attributed their lack of relation to the three-minute time constraint and emphasise on the quantity of responses during their task. Perhaps this increased the focus on timing, resulting in less creative responses (Zampetakis, Bouranta, & Moustakis, 2010). In comparison, the time limit in our study was 25 minutes. Alternatively, the differences between the results can be explained by the fact that Zabelina et al. (2015) reported on adults, while we report on children.

We found no evidence for an association between increased originality and reduced sensory or sensorimotor gating. It is likely that participants who experience less top-down control will think of more answers because such a state of dispersed attention facilitates idea generation (Hommel, 2012). Likewise, the conditioning P50 amplitude has been reported to negatively relate to verbal fluency before (Bak et al., 2017), indicating that people that respond more intensely to conditioning stimuli perform better when confronted with distractions. Hence, distracting, seemingly irrelevant stimuli may contain relevant information for tasks that require multiple solutions or during a creative drawing task such as the TCT-DP. In comparison, originality is more akin to convergent processes because it is about finding a solution that is most optimal or novel (Guilford, 1967). This process is different from the quantitative nature of fluency and flexibility. The ability to produce many (different) responses may indeed benefit from an attenuated sensory gating response because it is related to the preparation and incubation stage of creativity, which focusses on idea generation and assessing all action possibilities (Hadamard, 1945). The second two stages are more convergent; assessment of ideas takes place and the optimal response is selected. When selecting the most novel and original response, quality assessment takes place, incubation, originality and comparison take time, and top-down control and sensory gating might have to be more engaged (Hommel, 2012; Mednick, 1962).

Even though P50 suppression and PPI both measure psychophysiological gating, they are based on different physiological phenomena and brain regions, as is among others evident from an absence of associations between the measures (Koch, 1999; Oranje et al., 2006, 1999; Swerdlow, Geyer, & Braff, 2001). This might explain our lack of significant findings during the PPI analyses. Moreover, PPI and P50 suppression also respond differently to different ISIs (Oranje et al., 2006).

We found no relation between attention and sensory or sensorimotor gating. Perhaps attentional difficulties do not originate from a general gating deficit but rather from a specific problem with controlled attention (Bluschke et al., 2020; Conzelmann et al., 2010). For instance, a sample of 10-12-year-olds with ADHD did not show any differences in PPI during a passive listening task but when participants had to actively ignore the stimuli, an attenuated PPI response was observed (Hawk, Yartz, & Pelham, 2003). Furthermore, adults with ADHD had a lower PPI response compared to healthy controls when task instructions were to attend to the stimuli in the paradigm, but no group differences were found during the passive listening condition (Conzelmann et al., 2010). It is recommended that future studies compare both active and passive paradigms to detect possible differences in both creativity and attention. Indeed, it has been suggested that behaviorally observed attentional difficulties, as assessed in the current study, are more related to top-down attentional control deficiencies (Sergeant, Geurts, Huijbregts, Scheres, & Oosterlaan, 2003). In addition, the hypothesis that creative people can flexibly alter their inhibitory and attentional processes based on task demands also fits well with this idea (Ansburg & Hill, 2003; Martindale, 2007).

By investigating different psychophysiological measures, this study further refined scientific knowledge about the often cited distractibility of creative individuals (Brandau et al., 2007; Cramond, 1994). Results may help children that are easily distracted by motivating them in aspects of creativity and self-efficacy (White & Shah, 2011). However, the current study is not without its limitations. For instance, although we measured creativity in different ways, we did not include a specific convergent thinking task. The sample size in the PPI analyses was rather small and the children that were unable to complete the PPI paradigm due to the stimulus intensity may all have had attenuated sensory gating. Therefore, we might have lost data from an important subgroup.

In conclusion, this study shows evidence that although sensori(motor) gating and attentional difficulties are unrelated, creativity and quantitative measures of divergent thinking such as fluency and flexibility, are at least indirectly related to decreased sensory, but not sensorimotor gating. Further research is required to examine if this relation is generalizable to other age groups, creativity measures, and measures of sensory gating.

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Two sides of the same coin? Reduced cognitive control relates to more attentional difficulties and to higher creativity

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Abstract

While creativity has been identified as one of the skills necessary to thrive in the 21st century, it is still unknown what drives creativity on a neurocognitive level. Creativity has been associated with increased distractibility, but at the same time - and seemingly paradoxically- also with increased focused attention. This study focused on the diverse attentional processes involved in creativity and attentional difficulties. Healthy primary school children (N = 62) between 9 and 13 years old performed a selective attention paradigm while psychophysiological measures were recorded that measured cognitive control (P300), conflict monitoring (N200), and subconscious attentional shifts (Mismatch Negativity). Attentional difficulties were measured with a parental questionnaire and creativity measures were obtained by means of a divergent mathematical creativity task and a creative drawing task. We found that more creativity was related to decreased cognitive control (i.e. larger, more positive N200 and smaller P300 amplitudes), however without affecting task performance. In addition, attentional difficulties were related to more positive N200 amplitudes on the attended and non-attended standard trials of the selective attention paradigm, as well as reduced task performance. Our current data suggest that some creative processes such as originality are associated with decreased cognitive control, possibly to promote remote associations. Furthermore, our data shows that attentional difficulties are associated with a lack of selective attention and impaired information processing. Hence, although less cognitive control is often referred to in a negative way, it does seem to facilitate creative thinking without affecting task performance.

Keywords: Divergent thinking; Creativity; Selective attention; Cognitive control; Attentional difficulties

Introduction

As first described by Eysenck (1967) and later confirmed by Chakravarty (2010), the disinhibition hypothesis states that a creative, excitatory state stems from low levels of cortical arousal in frontal brain regions. This dispersed attentional state may be positively related to creativity, defined as making something novel and useful based on the situation (Plucker, Beghetto, & Dow, 2004). For instance, creative people have been associated with distractibility, atypical attention, ADHD, and schizotypy (Brandau et al., 2007; Carson, Peterson, & Higgins, 2003; Gonzalez-Carpio, Serrano, & Nieto, 2017; Hoogman, Stolte, Baas, & Kroesbergen, 2020; Nettle, 2006). However, accounts that creativity is related to the ability to focus attention also exist (Chrysikou, 2019; Fink & Benedek, 2014). Since creativity has been proposed as one of the skills to hone and perfect to thrive in the 21st century (Piirto, 2011), it is important to understand the underlying psychophysiological mechanisms. To investigate the underlying neurocognitive factors of creativity, divergent thinking, and attentional difficulties we examined the electrophysiological measures Mismatch Negativity (MMN), N200, and P300 event related potentials (ERPs) of healthy primary school children during a selective attention paradigm.

When a deviant stimulus is perceived in a sequence of standard stimuli, a subconscious, pre-attentive response is elicited in the brain 100-200 ms afterwards, called MMN (Näätänen, 1995; Umbricht & Krljes, 2005). It is visible as a negative deflection in frontal and temporal areas of the brain (Giard, Perrin, Pernier, & Bouchet, 1990) and linked to attentional shifts (Winkler, 2007). An extensive body of work found the MMN amplitude to be deficient in schizophrenia (Avissar et al., 2018; Brenner et al., 2009; Morris, Griffiths, Le Pelly, & Weickert, 2012; Oranje, Aggernæs, Rasmussen, Ebdrup, & Glenthøj, 2017; Rydkjær et al., 2017; Umbricht & Krljes, 2005) and, although less often, also in ADHD (Rothenberger et al., 2000; Rydkjær et al., 2017; Sawada, Negoro, Iida, & Kishimoto, 2008). When combined with the fact that individuals with higher ratings of ADHD symptoms are regularly better at creative tasks (Hoogman et al., 2020) and that creativity and schizophrenia seem positively related (Power et al., 2015) there is reason to believe that the MMN amplitude is associated with creativity.

The N200 ERP appears slightly later than MMN in the attentional process. It is a negative peak, that occurs in the frontocentral regions of the brain approximately 200 ms after stimulus presentation in response to conflict and conflict monitoring or mismatch detection even when no response is required (Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof, 2003; Yeung, Botvinick, & Cohen, 2004). Given this location and description, the N200 amplitude has been associated with cognitive control (Nieuwenhuis et al., 2003). Moreover, researchers have observed a significantly longer N200 latency in children with ADHD compared to healthy controls, signaling decreased cognitive control (Tsai, Hung, & Lu, 2012). However, as the stimulus discrimination process matures, this relation appears to fade (Barry, Johnstone, & Clarke, 2003).

The P300 amplitude relates to memory and attentional aspects of stimulus processing to inhibit excessive neural activation (Friedman, Cycowicz, & Gaeta, 2001; Polich, 2007). The P300 amplitude is composed of an early, more frontally oriented component, the P3A amplitude, and a later, more parietal oriented component, the P3B amplitude. The P3A amplitude is elicited when a distractor stimulus is presented and signals stimulus-driven, involuntary monitoring or switching of frontal attentional resources (Berti, 2016). The later P3B component is involved in attentional and cognitive control, necessary for task switching and is triggered when memory evaluation of a stimulus takes place because task relevant information is detected (Gajewski, Kleinsorge, & Falkenstein, 2010; Lange, Seer, & Kopp, 2017; Polich & Criado, 2006).

Although evidence is scarce, the P300 amplitude has been associated with one or more of the following characteristics: cognitive flexibility, task-set shifting, schizophrenia, and ADHD (Bramon, Rabe-Hesketh, Murray, & Frangou, 2004; Gow et al., 2012; Lange et al., 2017; Oja et al., 2016; Polich, 2007; Tsai et al., 2012). In its turn, cognitive flexibility has been associated with the prefrontal cortex, and creativity in some research (Barceló, Periáñez, & Knight, 2002; De Dreu, Nijstad, & Baas, 2011), but not in other research (Zabelina & Ganis, 2018). Hence, previous research seems to indicate that creative people are more adept in flexibly controlling their conscious attentional processes (Martindale, 2007; Zabelina & Ganis, 2018). This would allow them to constrict their cognitive and attentional filter when necessary. Thus, hypothetically, creative individuals may have altered pre-attentional activity, resulting in altered levels of the MMN amplitude, which would allow a greater number of environmental stimuli to be processed, yet more capacity to focus their attention to task relevant stimuli later on in the attentional process, resulting in larger N200 and P300 amplitudes, signaling increased top-down control (Conzelmann et al., 2010; Hawk, Yartz, & Pelham, 2003; Zabelina & Ganis, 2018; Zabelina, Sapora, & Beeman, 2016).

Therefore, in the current study, we investigated the association between early information processing, attentional difficulties, and creativity, by studying how these aspects are related to MMN, N200, and P300 amplitudes in a population of healthy children in the age of 9 to 13. We previously presented results of this same group of participants on sensory and sensorimotor gating (*Chapter 4*). In the current paper we will present the results on selective attention. Given the literature cited above, we first hypothesized that higher levels of creativity and/or attentional difficulties are related to altered MMN amplitudes. Second, we hypothesized that higher levels of creativity would be related to increased N200 and P300 amplitudes on deviant trials (when increased attentional cognitive control is required) whereas more attentional difficulties would be related to decreased N200 and P300 amplitudes, during the selective attention paradigm. Third, we examined task performance of the selective attention paradigm and compared it to the amount of attentional difficulties that parents reported their children to have in order to validate these measures. Hence, we expected a negative relation between attentional difficulties and task performance. Fourth, we also assessed processing negativity (PN) and P200 amplitude, for which we had no specific hypotheses.

Methods

Participants

70 participants that previously participated in a largescale behavioral study (N = 360) about creativity, mathematics, and executive functioning (Stolte, García, Van Luit, Oranje, & Kroesbergen, 2020) agreed to participate in the current study. Five participants did not perform the selective attention task caused by physical discomfort given that this task was at the end of our electrophysiological test battery. In addition, we excluded three participants from the analyses because of a suspicion or diagnosis of an autism spectrum disorder. In the analyses we had missing data for three participants on the attentional questionnaire, for two participants on the mathematical creativity test and for one participant on the Test for Creative Thinking-Drawing Production (Urban, 2004). Hence, 62 children were included in the final analysis. The sample included 33 boys (M_{age} = 10.76, SD_{age} = .78, Range = 9.42 – 12.47) and 29 girls (M_{age} = 10.89, SD_{age} = .87, Range = 9.52 – 12.72).

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Procedure

Participants performed The Copenhagen Psychophysiological Testbattery, which contains paradigms to measure P50 suppression, prepulse inhibition of the startle reflex, MMN, and selective attention (e.g. Oranje et al., 2017; Rydkjær et al., 2017). Participants completed the tests in a dimly lit and soundproof room after informed consent was obtained from a parent. Additionally, a test designed to detect possible hearing deficits was assessed by randomly presenting pure tones of 500, 1000, and 6000 Hz at an intensity of 40 dB for 40 ms across both ears. The test session lasted approximately two hours, of which 70 minutes was spend assessing the test battery. All study-procedures were approved by the Medical Ethical Committee of the Utrecht Medical Centre (NWMO18-849) and the Faculty Ethics Review Board (FETC18-081) prior to data collection.

Behavioral instruments

Mathematical creativity task. Creativity was measured with a divergent mathematical multiple solution task. This task is based on the test described in (Schoevers, Kroesbergen, & Kattou, 2018). In short, it contained three questions from an adapted and translated mathematical creativity test (Kattou, Kontoyianni, Pitta-Pantazi, & Christou, 2013; Schoevers et al., 2018) and one additional question from a different study (Hershkovitz, Peled, & Littler, 2009). To obtain a holistic measure of divergent thinking, questions were scored on originality, flexibility, and fluency (Leikin & Lev, 2013). The task has an acceptable internal consistency (Cronbach's α = .78; Kattou et al., 2013). Fluency refers to the total answers correct, flexibility to the different answer-categories, and originality to the uniqueness of an answer. To correct for the confounding effect of fluency on originality, we predicted originality from fluency and saved the residuals. Increases on any of these measures refers to more creative, divergent thinking in the domain of mathematics.

Test for Creative Thinking-Drawing Production (TCT-DP). A creative drawing test was administered to assess creative thinking The drawing contained six figural fragments and participants had 15 minutes to finish the drawing. Drawings were scored on fourteen creativity aspects, which were summed to one score. Hence, a higher score on the TCT-DP signals more creativity. Previous research has shown a high interrater reliability (r = .87) with an additional high differential reliability (χ^2 = 33.45, $C_{(corr.)}$ = .92; Urban, 2004).

Strengths and Difficulties Questionnaire (SDQ). We assessed whether children had attentional difficulties by letting parents complete the Strengths and Difficulties Questionnaire (SDQ). Answering options to the 25 questions were: "No", "A little", and "A lot". More attentional difficulties relates to a higher score on the subscale hyperactivity. A report on the internal consistency and validity showed satisfactory levels (Cronbach α between .65 – .88; Goodman, 2001; Mieloo et al., 2013).

Selective attention paradigm. The selective attention task contained 400 randomly presented stimuli. Stimulus presentation was randomized across the right and left ear. Stimuli were either standard stimuli (1000 Hz), which were presented in 80% of all cases or deviant stimuli (1200 Hz). The intensity of all stimuli was 75 dB for 50 ms with an ISI randomized between 700 and 900 ms. The participants were instructed to push a button as fast as possible when hearing a deviant stimulus in a previously designated ear. The task was performed twice, for monitoring in the left and right ear, lasting approximately 11 minutes. The amplitudes for PN, MMN, N200, P200, and P300 gave an overview of selective attention. That is, a less negative MMN amplitude is related to an attenuated response to deviant trails and a less negative PN amplitude signals that less attention was paid to stimuli in the to be monitored ear. In addition, more positive values on P200 and P300 amplitudes indicate increased processing of that trial type. Similarly, more negative values of N200 amplitude on a specific trial type signal increased processing of that trial type as well.

Data processing

Electroencephalography (EEG) recordings were made with BioSemi ® hardware (BioSemi, The Netherlands) containing 64 Active Two electrodes arranged according to the (extended) 10-20 system (Jasper, 1958). Signals were digitized at 2 kHz by a computer. The midline electrodes Fz, Pz, and Cz were used to analyse PN, MMN, N200, P200 and P300 amplitudes, all with average reference. We used BESA software (version 6.0, MEGIS Software, Gräfelfing, Germany) to process the data. We resampled the data from 2 kHz to 250 Hz and corrected the data for eye-artifacts with the adaptive method from BESA (Ille, Berg, & Scherg, 2002). Additionally, we removed any non-paradigm related artifacts, i.e. by removing trials where the difference in minimum and maximum amplitude exceeded 150μV in the relevant scoring window of 0 to 900 ms post-stimulus. Hereafter, data was epoched from 100 ms pre-stimulus to 900 ms post-stimulus and band-pass filtered (between 0.5 and 40 Hz). The MMN amplitude was expressed as the average ERP to deviant stimuli between 200 and 300 ms post stimulus. We expressed PN as the most negative difference between the ERPs to the attended stimuli subtracted by the ERPs to the unattended stimuli at electrode Fz between 250-350 ms. The averaged N200 (at Fz), P200 (at Cz), and P300 (at Pz) amplitudes were scored separately for each stimulus type (i.e. attended deviant (=target), non-attended deviant, attended standard and non-attended standard,). The N200 amplitude was scored between 200 – 300 ms, the P200 amplitude between 90 – 200 ms, and the P300 amplitude between 200-450 ms.

Analysis

We analysed the data in IBM SPSS Statistics 24. First, we performed Kolmogorov Smirnov tests to inspect the distribution of the data. Second, the strength of the relation between the EEG measures and behavioral responses (hits, misses, false alarms, and reaction time to hits), creativity and attention was determined with Spearman correlations. We inspected if age and gender were significant covariates. If this was not the case, they were omitted.

Results

Descriptive information on the amplitudes of the PN to standards MMN to non-attended stimuli, creativity and attentional measures is shown in Table 1. The amplitudes of the auditory N200, P200, and P300 amplitudes are presented in Table 2. Since all creativity and attentional measures were non-normally distributed (Kolmogorov Smirnov test), we proceeded with Spearman correlations to test our hypotheses.

Table 1 *Mean and standard error of processing negativity (PN), mismatch negativity (MMN), creativity, and attentional outcome measures.*

Measure	Mean	SE
TCTDP	22.42	1.34
Creative fluency	15.26	.95
Creative flexibility	7.52	.28
Creative originality	1.80	.08
SDQ	3.96	.33
MMN amplitude	-1.55	.15
PN amplitude	-.88	.08

Table 2 *Mean and standard error of the ERP amplitudes (uV) per stimulus type.*

ERP	Attended				Non-attended			
	Standard		Deviant		Standard		Deviant	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
N200	-2.80	.15	-3.57	.27	-2.82	.15	-3.44	.22
P200	3.08	.23	5.65	.32	3.20	.21	4.76	.29
P300	1.40	.12	4.45	.23	1.42	.12	3.31	.19

The relations between creativity, attention problems, and N200/P300 amplitudes are displayed in Figure 1. A significant negative correlation was found between the TCTDP and N200 amplitude to both attended (r_s = −.258, p = .045) and non-attended deviant trials (r_s = −.296, p = .020). Additional significant correlations were found between originality and P300 amplitude on the attended (r_s = −.291, p = .025) and non-attended deviant trials (r_s = −.325, p = .011). Furthermore, the scores on the SDQ and N200 amplitude were positively correlated on attended (r_s = .393, p .020) and non-attended standard trials (r_s = .291, p = .025). We found no significant correlations between MMN amplitude and any of the creativity or attentional measures (r_s < .193, p > .136) or between N200 and P300 amplitude and flexibility (r_s < -.171, p > .191) or fluency (r_s > -.182, p > .165). In addition, no significant correlations were found between creativity or attentional measures and PN (r_s < .219, p > .096) or P200 amplitude (r_s > -.234, p > .165).

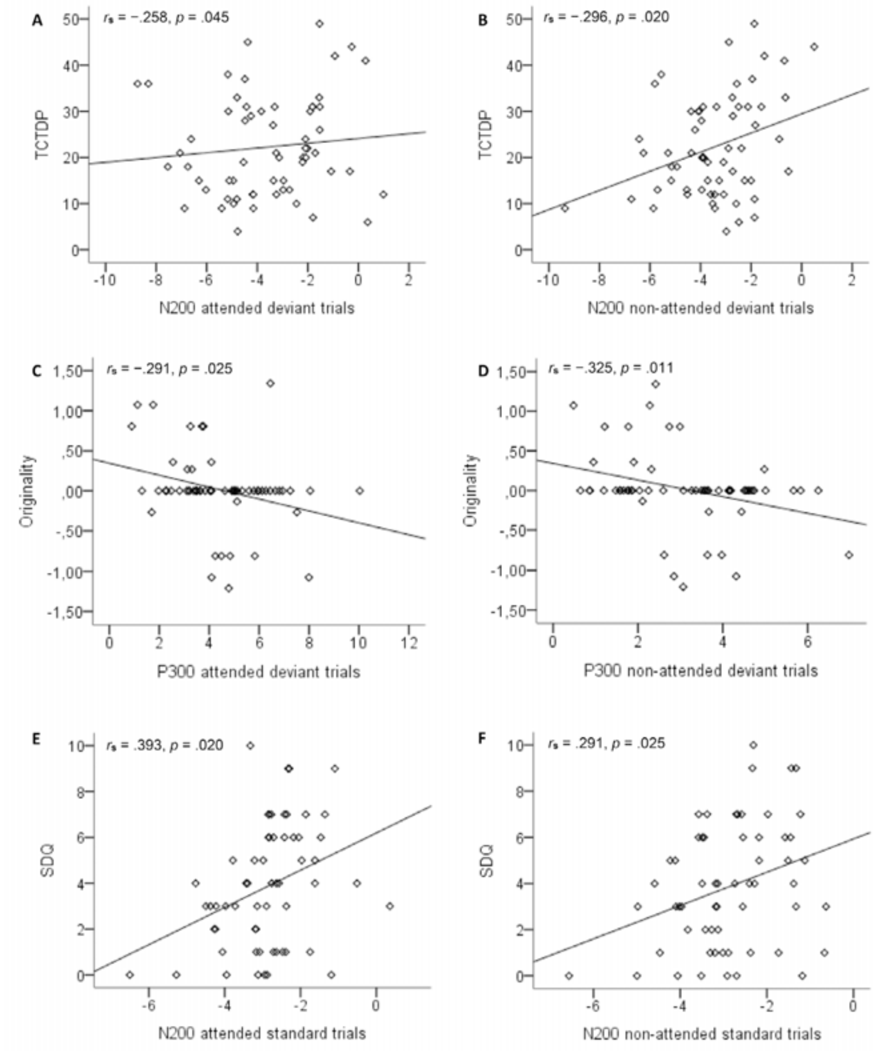

Figure 1. Scatterplots of the main significant Spearman correlations between the N200 & P300 amplitudes, creativity, and attentional measures ($p < .05$).

Panel A: TCTDP x N200 amplitude to attended deviant trials. Panel B: TCTDP x N200 amplitude to non-attended deviant trials. Panel C: Originality x P300 amplitude to attended deviant trials. Panel D: Originality x P300 amplitude to non-attended deviant trials. Panel E: SDQ x N200 amplitude to attended standard trials. Panel F: SDQ x N200 amplitude to non-attended standard trials.

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Because of the significant correlation between the N200 amplitude, P300 amplitude and the SDQ, we exploratively inspected the relation between the individual questions of the SDQ and these amplitudes. A significant correlation was found between the score on question 2 (being restless and overactive) and the N200 amplitude to the attended standard trials (r_s = .390, p = .0020), the non-attended deviant trials (r_s = .277, p = .032) and the non-attended standard trials (r_s = .374, p = .003), as well as the P300 amplitude to the non-attended deviant trials (r_s = .272, p = .036). Additionally, the scores on the question regarding being easily distracted was correlated with the N200 amplitude to the attended standard trials (r_s = .333, p = .009).

Since gender significantly correlated with originality, we used split file to inspect the relation between P300 amplitude and originality for boys and girls separately. Here, we only found a significant negative correlation between P300 amplitude to the attended deviant trials and the score on originality for boys (r_s = –.397, p = .027, n = 31) and not for the non-attended deviant trials (r_s = -.076, p = .616). For girls, we found neither a significant relation between P300 amplitude to the attended deviant trials and the score on originality (r_s = -.186, p = .334, n = 29) nor for the non-attended deviant trials (r_s = -.346, p = .066).

Behavioral performance on the selective attention paradigm was assessed with number of hits, false alarms overall and on standard or deviant trials. It was tested how these measures were related to attention difficulties (SDQ) and the creativity measures. No significant associations were found between any of the creativity measures and these performance measures (r_s < .187, p > .157). However, children who scored high on the SDQ, which assessed attentional difficulties, had significantly more false alarms (r_s = .314, p = .016). In addition, a negative correlation was found for amount of attentional difficulties and hits to target (= attended deviant) trials (r_s = –.444, p < .001). No significant differences were found between any of the creativity measures and reaction time to hits (r_s > -.182, p > .168).

Discussion

The current study reports the psychophysiological underpinnings for attentional difficulties and creativity in healthy primary school children. We investigated if there was an association between increased cognitive control and creativity on the one hand and decreased cognitive control and attentional difficulties on the other hand. We found that creative originality and performance on a creative drawing task were related to decreased cognitive control during a selective attention task, as measured by both larger (more positive) N200 and smaller P300 amplitudes on the attended deviant trials for higher values of creativity, contradicting our hypotheses. In addition, we found that less cognitive control, measured by increased (more positive) N200 amplitude on standard trial types, was related to more attentional difficulties as indicated by a higher score on the SDQ; a closer examination revealed that this association was predominantly based on the SDQ-sub questions of restlessness, overactivity and being easily distracted. Contrary to our predictions, there was no significant relation between MMN amplitude and creativity or attentional difficulties. Our behavioral results revealed that whereas creativity was not related to scores of hits or false alarms on the selective attention task, the presence of attentional difficulties was related to these scores.

In contrast to previous research, we found that higher levels of creativity were related to electrophysiological evidence of less focused attention and diminished cognitive control, in response to deviant, uncommon stimuli (Barceló et al., 2002; Zabelina & Ganis, 2018). However, in spite of this, no association was found between task performance (scores of hits and false alarms) and the creativity measures, indicating that children performed equally well on the task, regardless of creativity. Hence, it appears that more creative children do not appeal to their cognitive control processes as much as less creative children when they encounter stimuli that require their attention, while still performing equally well as less creative children. This agrees with the above mentioned disinhibition hypothesis by Eysenck (1967), at least for the currently assessed creative originality and creative drawing, probably by less cortical suppression of remote associations (Radel, Davranche, Fournier, & Dietrich, 2015). Perhaps an explanation for these differences in results is that time pressure leads to a different utilization of cognitive control processes since we allowed our participants more time to complete the creative tasks in comparison to previous research that found contradicting results (Zabelina & Ganis, 2018). In addition, creative achievements in daily life, that are less confined in terms of time, also seem to benefit from distractibility (Zabelina et al., 2016).

Creative, divergent thinking requires making numerous associations in order to increase the amount of responses (diversification based on fluency and flexibility). To increase this number of associations creative individuals can either increase the number of environmental stimuli reaching the association areas by opening up their sensory filters (bottom-up approach), or they can inhibit attentional or cognitive control allowing these associative areas more energy to combine the environmental stimuli that pass through these sensory filters anyway (top-down approach). We found no evidence for the bottom-up approach, as indicated by our current finding that MMN amplitude did not correlate with either creativity or originality. Furthermore, in our previous study on these same group of children we found no relation between sensory- and sensorimotor gating and originality or creative drawing and only a minor relation between sensory gating and flexibility and fluency (*Chapter 4*). Instead, our current finding that creativity appears related to less focused attention and diminished cognitive control points toward the top-down approach. This type of decreased cognitive control might be especially beneficial in the domain of mathematical creativity since people often think of mathematics as a fixed system which may make it even more difficult to think 'out-of-the box' in comparison to other domains. Interestingly, patients with schizophrenia are known for their so-called "loose associations" (DSM-5; American Psychiatric Association, 2013). Besides this, there are studies linking (subclinical levels of) schizophrenia with creativity (Acar, Chen, & Cayirdag, 2018; Kyaga et al., 2013), as well as numerous reports indicating both reduced sensory filtering and diminished N200 and P300 amplitudes (e.g. Bramon et al., 2004; Kim, Kwon, Kang, Youn, & Kang, 2004; Oranje & Glenthøj, 2013). In the light of the above top-down and bottom-up reasoning, this suggests that patients suffering from schizophrenia not only are flooded by sensory stimuli (caused by increased bottom-up processes), but also have overactive association areas (caused by decreased top down control) that need to try to make sense of all these stimuli, hence resulting in loose associations which in later stages develop in hallucinations and delusions (Perry, Geyer, & Braff, 1999); in other words: patients with schizophrenia may suffer from pathological levels of creativity or originality.

Contrary to our hypothesis, we did not find that the presence of mild attentional difficulties were associated with differences in MMN amplitude. Hence, this indicates that the automatic, pre-attentive identification system for deviant or unexpected stimuli is intact in children with mild attention difficulties. In the past, several studies reported relationships between attenuated MMN responses and clinical levels of attentional difficulties, such as present in individuals with ADHD (Kilpeläinen, Partanen, & Karhu, 1999; Rothenberger et al., 2000; Sawada et al., 2008). However, similar to our current results, this is not always found, also in previous studies from our lab (Gomes, Duff, Flores, & Halperin, 2013; Rydkjær et al., 2017). Some of these discrepancies might be explained by methodological differences such as (frequently) small sample sizes, differences in population (i.e. individuals with subclinical levels of attentional difficulties in comparison to individuals diagnosed with ADHD) ERP time window, and differences in task characteristics such as stimulus duration, frequency, and inter-stimulus interval. Moreover, others claim that pre-attentive measures such as MMN are not the cause of attentional difficulties but that deficits in later attentional processes are the root of such behavioral issues, which may also be true for creativity and would agree with our current results (Gomes et al., 2013; Sergeant,Geurts, Huijbregts, Scheres, & Oosterlaan, 2003).

Consistent with this line of thinking, we found that increases in attentional difficulties were indeed accompanied with smaller (more positive) N200 amplitudes on both attended and non-attended standard trials, indicating less inhibitory processing. Indeed, not only did we find that the presence of attentional difficulties were associated to these electrophysiological measures, it was also related to several measures indicating lower performance on our selective attention paradigm. Similar results have been reported before (Johnstone & Barry, 1996; Stroux et al., 2016), hence providing further evidence that impaired information processing is linked to impaired cognitive control (Cai, Griffiths, Korgaonkar, Williams, & Menon, 2019). This link between attentional difficulties and impaired cognitive control might correspond to deficits in the executive control network that have been extensively documented in children with ADHD (Francx et al., 2015; Lin, Tseng, Lai, Matsuo, & Gau, 2015), because these children usually show similar attentional difficulties.

Our current sample was too small to examine subgroups, but future studies could focus on gifted and learning disabled children or investigate the relation between creativity and psychophysiological properties in children with ADHD to inspect if the high levels of inattention in a clinically diagnosed sample are associated with reduced cognitive control and how this relates to creativity. Furthermore, we recommend investigating whether our results hold for other measures of creativity, such as creative achievements, since real-life creativity and standardized tests have led to different results in the past (Zabelina & Ganis, 2018). In addition, future studies should try to replicate our current MMN results with a paradigm without an (selective) attentional component. After all, it is conceivable that the lack of correlations between MMN amplitude and creativity as well as between MMN amplitude and attentional difficulties in the current study was caused by the children concentrating on performing well during our selective attention paradigm, creating a confounding factor of attention.

In conclusion, we found that less cognitive control in healthy children was related to higher originality and performance on a creative drawing task but not to differences in the quantitative measures of creativity, fluency and flexibility. In addition, while more attentional difficulties were related to less cognitive control and worse task performance during a selective attention task, task performance was not related to the level of creativity; suggesting that while creative children utilize less cognitive control on a neural level, this does not impair them behaviorally. These new insights into the underlying cognitive component processes of creativity provide important knowledge about how a more dispersed attentional state is best to encourage and develop children's creative potential.

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Summary and general discussion

The title of this dissertation, *(In)attention for creativity*, refers to two central topics of this PhD project: (1) more *attention* should be placed on creative, divergent thinking in primary education and (2) *inattention* or distractibility might actually be a positive attribute for creativity. This dissertation contributes to the increasing knowledge that is available on (mathematical) creativity, attentional and sensory gating processes, and executive functioning in children, and it also extends this knowledge by combining the theories and tools from educational sciences with methods from cognitive neuroscience. To accomplish this, two behavioral studies were conducted at school with healthy primary school children between 8 and 13 years of age (see *Chapters 2* and *3*). Subsequently, a subset of these children also participated in a study that was performed in a lab setting in which electroencephalography (EEG) and electromyography (EMG) measurements were obtained (see *Chapters 4* and *5*). In this final chapter, the main findings are summarized and discussed in relation to one another. Based on these main findings, directions for future research are proposed and the implications are discussed.

Summary of the main findings

In *Chapter 2*, we analyzed the behavioral data from our first behavioral child study (*N* = 82) in which we investigated the relation between mathematical ability, mathematical creativity, and inhibition. Although previous research revealed that executive functions are important for mathematical achievements (Friso-Van den Bos, Van der Ven, Kroesbergen, & Van Luit, 2013), it was not clear how the executive function inhibition relates to mathematical creativity. Empirical research had found contradicting evidence that adequate inhibition is related to more creativity (Benedek, Franz, Heene, & Neubauer, 2012) but also that reduced inhibition is beneficial for creativity (Burch, Hemsley, Pavelis, & Corr, 2006). Since these studies had analyzed the direct relation between these two variables, we hypothesized that this difference in results might be explained by the fact that inhibition would moderate the link between mathematical ability and mathematical creativity. In our first study, the participating children performed a mathematical multiple solution task that measured divergent thinking in the domain of mathematics. Answers were scored on fluency (the number of correct answers), flexibility (how many answer categories were used), and originality (the novelty of an answer based on a reference group). Furthermore, inhibition was measured with a Flanker task (Eriksen & Eriksen, 1974) to investigate the influence of incongruent flankers on the average response time.

The results revealed a direct relation between mathematical ability and mathematical creativity but no direct relation between inhibition and mathematical creativity. However, inhibition did act as a moderator, strengthening the relation between mathematical ability and mathematical creativity for flexibility and originality when inhibition was reduced. Furthermore, we found that for children with low mathematical abilities, reduced inhibition was detrimental for creativity. A possible explanation for this result is that these children actually have a double impairment: they do not have much mathematical abilities to use creatively, and on top of that, their reduced inhibition makes it challenging to inhibit unoriginal or previous responses and to stay focused on the task, further increasing the difficulty of this task (cf. Gilhooly, Fioratou, Anthony, & Wynn, 2007). Contrary to this double dissociation, we found that the performance of children with high mathematical abilities actually benefited from reduced inhibition, presumably because the high mathematical abilities lowered task demands and the reduced inhibition facilitated using these abilities and knowledge flexibly and originally.

In *Chapter 3*, these results were extended in a large-scale cross-sectional study (*N* = 278) in which the role of all three executive functions in mathematical creativity was studied by means of structural equation modelling. The same mathematical multiple solution task as described in *Chapter 2* was used to measure mathematical divergent thinking. This time, we did not examine the creative components fluency, flexibility, and originality separately but created a latent variable for mathematical creativity instead. In addition to inhibition, we also analyzed the influence of executive functions shifting and updating on mathematical creativity. Moreover, the relation between mathematical ability and general creativity on mathematical creativity was also examined. Since it had been established that well developed updating skills are beneficial for mathematics (Friso-Van den Bos et al., 2013; Van der Ven, Kroesbergen, Boom, & Leseman, 2012) and for creativity (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014), we hypothesized that it would also play a substantial role during mathematical creativity. In addition, although inhibition and shifting have been linked to mathematical ability in some studies (Chamandar, Jabbari, Poorghorban, Sarvenstani, & Amini, 2019; Yeniad, Malda, Mesman, Van IJzendoorn, & Pieper, 2013), Van der Ven and colleagues (2012) showed that this relation was no longer significant once the shared explained variance of updating was considered. Hence, we decided to compare two models using structural equation modelling. First, we tested whether mathematical abilities, general creativity, shifting, updating, and inhibition all had a direct influence on mathematical creativity. Second, we tested a model with two additional assumptions, namely that updating also influenced mathematical creativity indirectly through its influence on mathematical ability and general creativity. This second model fitted our data best. Besides, although mathematical ability, general creativity, inhibition, and shifting all had a significant, moderate correlation to mathematical creativity, none of these variables had a significant relation with mathematical creativity once updating was added to the model. Updating is probably important for creativity, mathematics, and mathematical creativity because it makes it possible to store intermediate steps and answers in working memory.

Together, these findings demonstrate the importance of including all three executive functions in the model to account for their shared variance. Although inhibition and shifting have been identified as unique facets of executive functions, they seem to be subservient to updating during mathematical creative thinking as they might explain more about the process of updating or what information is updated instead of representing distinct features.

In *Chapter 4*, we examined how differences in sensory gating and sensorimotor gating related to creativity. We applied a psychophysiological test battery that contains a sensory gating paradigm (n = 65) and a sensorimotor gating paradigm (n = 37) in a sample of healthy children. Given the hypothesized link between creativity and distractibility, analyses were performed to investigate whether lower sensory gating and sensorimotor gating were related to increased levels of creativity. It was expected that reduced P50 suppression (a measure of sensory gating) and prepulse inhibition of the startle reflex (a measure of sensorimotor gating) would facilitate creativity by gating in a wider range of stimuli to use creatively. It was observed that children with a higher response to the testing stimuli, as measured by a higher P50 amplitude, had higher scores on fluency and flexibility but not on other creativity measures. No other significant differences were found when groups were differentiated on other sensory gating measures or sensorimotor gating outcomes apart from higher creativity in the lower sensorimotor gating group on one specific trial type. Subsequently, we also examined whether attentional difficulties, as reported by parents on a questionnaire, were related to reductions in sensory gating or sensorimotor gating; however, no significant group differences were found when groups were based on sensory gating measures or sensorimotor gating measures.

In sum, these findings suggest that while some measures of creativity that are associated with generating multiple responses might be linked to some measures of reduced psychophysiological gating, other measures of creativity related to novelty and originality are not. Moreover, attentional difficulties are unrelated to sensory gating and sensorimotor gating and may instead be related to specific attentional deficits later in the perceptual process (Bluschke et al., 2020; Conzelmann et al., 2010).

Finally, in *Chapter 5*, we focused on how cognitive control, as measured with a selective attention paradigm, related to creativity (N = 62). Since the results in *Chapter 4* revealed that creativity is only marginally related to reduced sensory gating or sensorimotor gating, we hypothesized that creative differences might not be the results of these pre-attentive measures of awareness but that differences in conscious attentional processes might be the bedrock of creative potential instead. Creative originality and performance on a creative drawing task (related to creative potential; Urban, 2004) were associated with reduced cognitive control as indicated by larger N200 amplitudes and smaller P300 amplitudes on the attended deviant trials. No significant relation was found between the mismatch negativity amplitude and any of the creativity measures. Surprisingly, creativity measures were not related to task performance on the selective attention tasks. An additional question we addressed in this chapter was whether attentional difficulties were related to reductions in cognitive control in healthy primary school children. We found that more attentional difficulties were related to less cognitive control. No significant differences were found between P300 amplitude or mismatch negativity and attentional difficulties.

To conclude, the results discussed in *Chapter 5* point toward a positive role of reduced cognitive control for creative thinking without affecting task performance. This is in line with results by Radel, Davranche, Fournier, and Dietrich (2015) who found that reduced cognitive control promotes idea generation, possibly by disinhibiting remote association areas in the brain.

The four studies described earlier allow for four main conclusions to be drawn. First, inhibition serves as a moderator between mathematical abilities and mathematical creativity, with the contribution of inhibition varying for children with high and low mathematical abilities and the aspect of creativity under investigation. Second, the executive function updating has a direct and an indirect positive relation to mathematical creativity. In addition, the other executive functions, i.e., inhibition and shifting, do not have a significant direct relation to mathematical creativity when the shared variance with updating is considered. Third, although the subconscious attentional measures of sensory gating, sensorimotor gating, and mismatch negativity are not or only marginally related to creativity, conscious measures of attention and reduced cognitive control are related to higher creativity without affecting task performance. Fourth, attentional difficulties in healthy children stem from a specific attentional impairment in cognitive control and conflict monitoring and not from reduced sensory or sensorimotor gating.

General discussion

The aim of this PhD project was to elucidate the role of mathematical abilities, inhibition, shifting, updating, cognitive control, and psychophysiological gating in (mathematical) creativity in healthy primary school children. A multimethod design was employed to look into the underlying factors of (mathematical) creativity by studying behavioral data, questionnaire data, and (neuro)cognitive factors of attention and executive functions as it is becoming increasingly accepted that mental processes take place, not only in relation to the person but also in relation to the outside world, the physical properties of a person, and the sociocultural belief system that someone has (Barsalou, 2008; Corazza & Glăveanu, 2020; Glăveanu, 2020; Stoffregen, 2003; Van Dijk, Kroesbergen, Blom, & Leseman, 2019).

Currently, it is believed that reduced inhibition and distractibility are not conducive to success, and thus, teachers try to develop and increase the attentional capacity of their students during primary school (Bolden Harries & Newton, 2010; UNESCO, 2012), failing to promote creative and divergent thinking. The main goal of this dissertation was to investigate if reduced inhibition and decreased cognitive control might actually be beneficial to creative activities for children (*Chapters 2, 4,* and *5*) and should therefore also be encouraged in education and daily life. Since creativity only plays a small role in current theories of development and learning, and an emphasis is mostly placed on the importance of convergent thinking and focused attention instead of divergent thinking and distributed attention, creativity only takes up a small part of current teaching programs, tests, and textbooks (Espy et al., 2004). Consequently, children's creativity seems to decline during primary school (Kim, 2011; Krampen, 2012). Furthermore, this may be the reason that highly creative children often display underachievement on standardized school tests or receive incorrect diagnoses of behavioral disorders because the classroom climate does not fit their needs and qualities (Carson, Peterson, & Higgins, 2003; Kroesbergen, Van Hooijdonk, Van Viersen, Middel-Laleman, & Reijnders, 2016). Situations in real life often pose complex and unfamiliar problems for which the ability to think creatively and outside-the-box are necessary. Therefore, the current results hold a significant value for educational purposes because the main goal of education is to prepare children to thrive in society (Sternberg, Lubart, Kaufman, & Pretz, 2005).

With the results of our study (*Chapter 2*), we have shown that in some instances and for some children this distractibility or reduced inhibition and an encouragement of less focused attention might be better suited to their abilities. That is, for divergent thinking to go well, children who have enough general (non-creative) abilities in a domain actually benefit from reduced inhibition, and perhaps these children will also benefit most from reduced cognitive control to disinhibit remote associations. In addition, these children may benefit from a very stimulus-rich environment when they have to think divergently. This may lead to changes in how schools design their classrooms and lessons or in what setting certain lessons are taught. Supposedly, the opposite is true for children with low levels of general abilities in a domain. These children possibly benefit more from being in a structured environment and from better inhibitory skills to overcome their lack of abilities and be creative. Hence, reduced inhibition or dispersed attention can only be beneficial in case of a sound knowledge base, not only during creative thinking but also in general by providing compensation for such deficits (Milioni et al., 2017). However, this does not mean that children with low (mathematical) abilities or reduced inhibition should be excluded from creative tasks. In fact, creative thinking may be a prerequisite for the development of more general abilities because creatively applying knowledge and abilities can potentially lead to a deeper understanding of the domain (Bahar & Maker, 2011; Kattou, Kontoyianni, Pitta-Pantazi, & Christou, 2013; Leikin, 2007), which makes creative tasks even more important for children with low abilities. As such, primary school teachers should be aware of a child's strengths and weaknesses and adjust their lessons accordingly. For instance, it might be helpful to screen for reduced inhibition and differentiate the teaching style based on this quality. Perhaps children with low abilities in combination with reduced inhibition could be more creative when they receive slightly more instruction and feedback from their teacher or by including more constraints in the task (Bokhove & Jones, 2018). In addition, these children may benefit from working on the task with another child (Leikin, 2007) as another way of scaffolding and to lower the executive strain of the task demands.

In *Chapters 2* and *3* of this dissertation, we presented results that indicate a positive association between mathematics and creativity. Because creativity in the classroom is limited in mathematics, mathematics education is frequently reduced to mastering a set of skills and procedures that can be memorized but not easily applied in a flexible or original manner. Since children are naturally creative, the emphasis on direct instruction and convergent thinking may cause children to lose their innate curiosity and enthusiasm for mathematics as they move through the education system. In a report by the U.S. Department of Education, 81% of fourth graders report a positive or strongly positive attitude toward mathematics (Sherman, Honegger, & McGivern, 2003). However, four years later these numbers have decreased to 35% of eight graders who still report a positive attitude toward mathematics. This creates a shortcoming for the children themselves because mathematics and (mathematical) creativity is needed to solve the problems of contemporary society (National Council of Teachers of Mathematics, 2000; Piirto, 2011). Additionally, the large focus on convergent thinking also produces a challenge for the teachers that are trying to instill divergent thinking and creativity while teaching mathematics (Meissner, 2000). Although teachers stress that learning several methods to solve mathematical tasks and combining different mathematical ideas (two important aspects of divergent thinking) are crucial elements for developing mathematical reasoning (National Council of Teachers of Mathematics, 2000), this is often not implemented in class because the teach-to-the-tests method, which focusses on learning rote knowledge and procedures, diminishes the time to develop divergent thinking skills in mathematics (UNESCO, 2012). Hence, because the main focus during mathematical lessons is generally placed on standardized, algorithmic-based methods and convergent tasks (Kim, 2011; Kim, Cho, & Ahn, 2004; Kwon et al., 2006) children might not fully develop their creative potential and divergent thinking skills. If mathematical creativity becomes more embedded in educational programs, for instance by incorporating more multiple solution tasks or open-ended assignments, children might view mathematics in a more positive way, which will make them better prepared to tackle real-life problem-solving situations, which often require a combination of creativity (Leikin & Pitta-Pantazi, 2013; Silver, 1997) and mathematics (National Council of Teachers of Mathematics, 2000).

A commonly used definition of creativity was proposed by Runco (2004). He stated that creativity is “the production of something novel, useful, and appropriate.” With this definition, he stepped away from the focus on objective terms when defining creativity, facilitating a huge leap in the conceptualization of creativity. Oftentimes, creativity is measured by the creative product, possibly because it is easiest to measure. A distinction of these products, whether they are a sculpture, a manuscript, or a performance, is that in some social context, the product is judged to be valuable in some way. However, when creativity is defined in this manner, the underlying process and the personal environment and belief systems of the maker are overlooked. What are the prerequisites for creativity? In compliance with the sociocultural, perception-action approach to creativity (Corazza & Glăveanu, 2020), the studies in this dissertation describe that conscious attentional processes and executive functioning contribute to the extent to which a child can perceive and process their environment and abilities to use creatively. More specifically, the knowledge and skills within a domain that a child already possesses will form the base for creative thinking. Additionally, inhibition of unoriginal thoughts and old strategies will facilitate creative thinking if the knowledge threshold for creativity is not reached (*Chapter 2*; Jauk, Benedek, Dunst, & Neubauer, 2013). In addition to knowledge or abilities, another area that provides affordances is the environment. Hence, creativity is influenced by environmental factors (Corazza & Glăveanu, 2020; Van Dijk et al., 2019) and how well a child can perceive and process information. We found that the subconscious filtering processes of sensorimotor gating and sensory gating were not or only marginally related to creative outcomes (*Chapter 4*) but that conscious attentional processes of cognitive control were related to creativity (*Chapter 5*).

Furthermore, executive functions, in particular updating seems to regulate the utilization of affordances from previous knowledge, abilities, and the environment (*Chapter 3*).

These results add further evidence to the idea that creative thinking is mostly a top-down process, i.e., not merely related to the sensory information that is perceived but largely driven by higher order cognitive functions such as executive functions and by prior knowledge (Zabelina, Colzato, Beeman, & Hommel, 2016). Following this idea, creative thinking is a skill that can be fostered, reserving a promising role for education. Based on the findings presented in this dissertation, we visually present our adapted view of creative cognition in Figure 1. The figure shows the multiple underlying processes that influence creative and divergent thinking. What can be seen here is that the amount of affordances that are perceived and accordingly information present in working memory storage depends on (1) the type and amount of (domain) knowledge and abilities or intelligence that can be used for creative thinking; (2) the environment in which a creative task has to be completed; (3) the amount of cognitive control and selective attention to inhibit remote association areas of the brain (due to cortical disinhibition) and overcome a fixed mindset; (4) (to a lesser extent) sensory gating mechanisms that filter stimuli from the environment; (5) working memory capacity; (6) how well the working memory storage is updated with new, relevant information; (7) reduced inhibition to be flexible and original when a strong knowledgebase is present; and (8) what type of information is brought into working memory storage through updating depends on knowledge or intelligence (as well as cultural beliefs), as this will relate to heuristics in judging what is relevant and what is not.

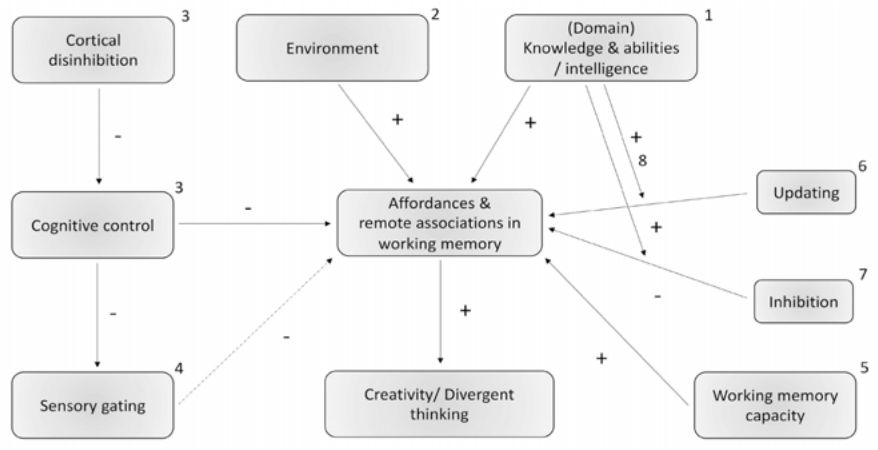

Figure 1. A possible model for creative thinking.

Note. Arrows point to a moderate to strong relation, the dotted arrow signifies a small relation. The minus signs indicate a negative relation between two constructs. The plus signs indicate a positive relation between two constructs.

In this regard, we adopt the multifold classification of creative potential as defined by Corazza and Glăveanu (2020). Hence, although an environment has the potential to lead to creative acts or a person has sufficient knowledge and abilities that they can use creatively, this does not always lead to a creative outcome and is based on the interaction of all the elements involved in the creative processs. This dissertation contributes to the accumulating evidence that creativity is, for a large part, a top-down process that relies on various higher order cognitive functions such as executive functions and cognitive control. Further research is necessary to fully validate with empirical results the proposed alternative model depicted in Figure 2.

Future directions

Because the studies presented here are cross-sectional, an outstanding question for future research is if the implied causal relations are indeed present. Therefore, longitudinal and experimental research is desirable to see how the relation between the executive functions, that are still developing in primary school children (Huizinga & Van der Molen, 2006; Van der Sluis, De Jong, & Van der Leij, 2007; Van der Ven et al., 2012), and mathematical creativity develops over time. Young children are not yet aware of the various strategies to solve math problems. However, as children develop, the type of mathematical tasks changes as do the necessary strategies and knowledge to complete these tasks. Moreover, mathematical tasks also become more complex and may involve several steps and intermediate answers. Stated this way, perhaps the executive functions of shifting will become more important for more complex mathematical creativity tasks and when children's mathematical ability is further advanced when they are older. A limitation of this dissertation is that we only used one mathematical multiple solution task to study mathematical creativity, but hypothetically speaking, and building on our results from *Chapter 2*, reduced inhibition might also become more advantageous as mathematical abilities increase. Shifting may facilitate creative answers more during multi-step mathematical creativity tasks in comparison to a multiple solution task. Therefore, we recommend that future research investigates a broader range of tasks to measure the whole construct of mathematical creativity.

Although this dissertation contains innovatory results about the cognitive and neurological underpinnings of (mathematical) creativity, it was beyond the scope of this PhD project to investigate how to implement our findings in education to facilitate the development of creative divergent thinking. However, much is still unknown about how best to stimulate the development of creative skills within the educational system and more specifically during mathematics education. Stimulating creativity can be operationalized in several ways, for example: Giving children tasks that they have not studied previously in class and are novel to them; asking children to solve mathematical tasks in different ways, which will lead to new knowledge; or posing problems that are related to the one that was being solved (Leikin, Koichu, & Berman. 2009). Regarding these elements of stimulating and developing creativity, teaching creativity is often not done in a direct way, but rather indirectly. This might be implemented by providing children with an environment that promotes thinking outside-the-box, challenges rules and procedures, and facilitates taking risks and imagining new and original ideas, all of which possibly rely on executive functions and reduced cognitive control. In response to this, a variety of creativity tests have been developed (e.g., Barbot, Besançon, & Lubart, 2011; Hershkovitz, Peled, & Littler, 2009). Unfortunately, these tests often do not focus on applying the knowledge that a child already possesses and can use in a creative way. This is problematic because some knowledge of a subject is required to engage in creative tasks, especially when inhibition is reduced, as we have shown in *Chapter 2* and *3*. Furthermore, if these tests wish to evaluate a child's creative ability in real life, a challenge for future research is to include the element of how prior knowledge is used in the assessment and to identify the knowledge threshold at which a child can successfully complete creative tasks. For instance, this could be achieved by semi-structured interviews with the participants to gauge how they tackled the mathematical creativity task or with a questionnaire. In addition, creativity tests are often challenging to administer in a classroom setting or difficult to properly rate by teachers, which makes them difficult to use in an educational setting (for a meta-analysis, see Gralewski & Karwowski, 2019). Now that we are aware of the underlying factors of creativity, novel tasks should be created and validated to accommodate divergent thinking in the classroom. For example, such tasks could actively reiterate the value of creativity, originality, and outside-the-box thinking (Schoevers, 2019). To achieve this while keeping our results in mind that updating and reduced cognitive control play a role in (mathematical) creativity, we recommend creating an open atmosphere and open opportunities that are not specifically targeted to any learning goals (Schoevers, 2019). In addition, during the tasks teachers could encourage children to think of multiple answers, think divergently, use their surroundings, use their imagination, take risks, and inspect different action possibilities for the elements of the task.

While the results in *Chapter 3* revealed that updating plays a large direct role in mathematical creativity and an indirect role, a limitation of this dissertation is that the sample size of our study was too small to investigate how the executive functions of shifting and updating relate to the different components of divergent thinking (i.e., fluency, flexibility, and originality). High performance on the fluency variable can possibly also be achieved with low knowledge and abilities by using only one strategy. For instance, in our mathematical creativity task, one question was to start with the number 7 and make a calculation that had 21 as the answer. Because the task instruction specifically stated to give multiple answers if this was possible, most children first wrote down the most obvious answer (7x3 = 21) and either stopped there, not providing multiple solutions, or continued by writing down various similar answers that were made different from each other based on a simple rule (for example 7+7+6+1 = 21 and 7+7+5+2 = 21 etc.). This results in high fluency but does not increase flexibility or originality. When using this strategy, executive functioning might be less involved because the items in working memory storage do not have to be updated, strategies do not have to be shifted, and previous answers do not have to be inhibited as much. Perhaps children with low executive functions and low domain knowledge or abilities resort to these types of divergent thinking strategies and do the best they can within their executive abilities. Moreover, our results are limited to our divergent multiple solution task, and the role of executive functions in mathematical creativity tasks that measure convergent thinking may be completely different (Hommel, 2012). When one optimal solution must be found and idea evaluation takes place, executive functions and cognitive control that keep a person focused on the task might be more advantageous (Chermahini & Hommel, 2010).

Another interesting question is to what extent the findings of our results presented in this dissertation are generalizable to subgroups and atypical populations. While our results provide a first look into the role of executive functions, psychophysiological gating, and cognitive control on (mathematical) creative thinking, a limitation of our study was that our sample was restricted in age, so our findings can only be cautiously extended to other age groups. In addition, the result that reduced cognitive control (and to a lesser extent reduced sensory gating) is positively correlated with creativity leads to the question of whether this might be why creativity has frequently been associated with mental illnesses with symptomology of distractibility or reduced cognitive control in the past such as schizophrenia and ADHD (for a review, see Hoogman et al., 2020; Kyaga et al., 2013). Our results suggest that having slightly lower levels of cortical activation could lead to more creativity by reduced cognitive control leading to more stimuli in the mental processes. However, certain protective mechanisms need to be in place when performance is also impaired as shown in *Chapter 2*. Hence, such a reduction of inhibition is only conducive to creativity when sufficient domain general abilities are present. Similarly, when cortical disinhibition reaches pathological levels in which cognitive control, sensory gating, and sensorimotor gating are reduced to a much larger extent, too much strain might be put on the mind, leading to psychopathology instead of creativity. Within ADHD research, this distinction between subclinical and clinical levels of distractibility and its effect on creativity was confirmed (for a review, see Hoogman et al., 2020), and similar reports have been proposed for schizophrenia and schizotypy (Fink et al., 2014; Kinney et al., 2001). However, additional research is necessary to examine if this result can be replicated with diverse and more convergent measures of creativity and at what level decreased cognitive control is still beneficial and when it becomes detrimental and why, as observed in patients with schizophrenia, for example (Oranje & Glenthøj, 2013; Perry, Geyer, & Braff, 1999).

Finally, with regard to the superior flexible adaptation of attentional processes that has been theorized to be present in highly creative individuals, future research could investigate passive and active listening paradigms in combination with EEG measurements. If it is true that highly creative individuals are more adept at flexibly controlling their conscious attentional processes based on task demands (Ansburg & Hill, 2003; Martindale, 2007), creative people might show increased cognitive control and focused attention during a task with active listening demands but will show similar or reduced cognitive control and distractibility during a task with passive listening commands. In addition, if the task instructions are to be creative, perhaps a state of reduced cognitive control will be present. That being said, such superior flexibility might require certain regulatory mechanisms to be in place. A limitation of our studies described in *Chapters 4* and *5* was that our sample sizes were not large enough to create subgroups. A possible avenue for future research might be to investigate if certain regulatory mechanisms, such as increased intelligence or larger working memory storage, might moderate the association between sensory gating, cognitive control, and creativity.

Conclusion

In conclusion, this dissertation provides a comprehensive overview of the underlying cognitive and neurological factors of (mathematical) creativity in healthy primary school children and shows there should be more attention paid to the benefits of inattention for creativity. Our results hold value for the debate about the importance of reduced inhibition and dispersed attention for creativity. In addition, these results provide evidence that schools might do well to provide a more balanced approach to teaching mathematics in which creativity and divergent thinking are equally promoted to convergent thinking, while taking mathematical abilities into account. Based on our initial results, new theoretical frameworks can be constructed and empirically tested, which may eventually lead to the implementation of novel creativity tasks and educational practices that are better suited for the creative child.

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A

Addendum

Nederlandse samenvatting

Summary in Dutch

Vroeger werd creativiteit gezien als het resultaat van een bewust, intensief proces en werd het voornamelijk gerelateerd aan uitzonderlijke creatieve resultaten op het gebied van de kunsten, zoals schrijven, muziek en schilderen. Dit soort creativiteit was slechts weggelegd voor een selecte groep mensen met speciale vaardigheden (McWilliam, 2009). In deze definitie wordt creativiteit gezien als iets dat relatief stabiel is over de tijd heen en sterk verschilt per persoon. In de achttiende eeuw werd de basis gelegd voor de moderne creativiteit door te stellen dat hoogbegaafdheid en bovennatuurlijke vermogens losgekoppeld waren van creativiteit en dat dit iets is wat iedereen kan ontwikkelen, zij het in verschillende mate. Dankzij deze nieuwe visie werd creativiteit iets dat men kon leren en stimuleren, bijvoorbeeld op school. Een mogelijke definitie van dit soort creativiteit is een interactie tussen de vaardigheid van een individu of van een groep, het proces en de omgeving, die leidt tot het creëren van iets nieuws en origineels (tastbaar of abstract) dat een probleem kan oplossen, een bepaald doel heeft, of een bepaalde vraag kan beantwoorden (Plucker, Beghetto, & Dow, 2004; Runco & Jaeger, 2012). Daarnaast kan vanuit het socio-culturele perspectief op creativiteit gesteld worden dat creativiteit, net als andere cognitieve processen, zal verschillen tussen personen en omgevingen (Barsalou, 2008; Corazza & Glăveanu, 2020). Met andere woorden: creativiteit is een proces dat plaatsvindt in interactie met het brein, de persoon, het lichaam en de omgeving (Stoffregen, 2003; Van Dijk, Kroesbergen, Blom, & Leseman, 2019).

Hoewel creativiteit en rekenen op het eerste gezicht weinig met elkaar te maken lijken te hebben, zijn deze concepten juist nauw aan elkaar verwant. Kinderen kunnen bijvoorbeeld op individueel niveau creatief zijn op het gebied van rekenen als ze een bepaalde strategie voor de eerste keer bedenken en creativiteit is ook nodig om de grote wiskundige vraagstukken op te lossen (Bolden, Harries, & Newton, 2010; Sriraman, 2004). Helaas ligt de nadruk op school, en voornamelijk binnen de rekenles, op gestandaardiseerde methodes en convergente taken in plaats van op divergent en creatief rekenen (Kim, Cho, & Ahn, 2004; Thijs, Fisser, & Van der Hoeven, 2014) terwijl creativiteit wel wordt gezien als één van de belangrijkste vaardigheden om goed te kunnen functioneren in de 21e eeuw (Bell, 2010; Piirto, 2011). Deze ontmoediging en onzichtbaarheid van creativiteit zou de afname van creatieve vaardigheden tijdens de basisschool (Kim, 2011; Krampen, 2012) kunnen verklaren. Bovendien vinden studenten en docenten het vaak moeilijk om creativiteit te relateren aan rekenen en wiskunde, maar hebben ze dit probleem niet op andere domeinen (Kaufman & Baer, 2004). Door meer te weten te komen over de onderliggende factoren van creatief rekenen en over hoe creativiteit en rekenen aan elkaar gerelateerd zijn zou een basis gelegd kunnen worden voor een betere integratie van deze belangrijke 21e eeuwse vaardigheden in het basisonderwijs.

Aangezien executieve functies essentieel zijn voor doelgericht gedrag en flexibel gedrag, wordt er verondersteld dat ze gerelateerd zijn aan en voorspellend voor andere vaardigheden waarin flexibiliteit een belangrijke rol speelt zoals bijvoorbeeld bij creativiteit (Davidson, Amso, Anderson, & Diamond, 2006; Rhoades, Greenberg, Lanza, & Blair, 2011; Van der Sluis, De Jong, & Van der Leij, 2007). Vanaf het moment dat kinderen naar de basisschool gaan, moeten zij een groot aantal nieuwe technieken, regels, en strategieën te leren. Tijdens het ontwikkelen van deze vaardigheden moeten kinderen zich kunnen concentreren en niet te veel afgeleid worden, de informatie die ze absorberen begrijpen, deze informatie opslaan en hun herinneringen over het onderwerp bijwerken. Bovendien wordt van hen verwacht dat ze deze nieuw-aangeleerde vaardigheden kunnen toepassen in nieuwe situaties binnen en buiten de school en dat zij dit op een flexibele manier kunnen doen. Voor al deze stappen zijn executieve functies cruciaal. De executieve functies zijn in meerdere verschillende componenten te verdelen, zoals inhibitie, updaten en switchen (Davidson, et al., 2006; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Inhiberen is het kunnen onderdrukken van een automatische, voor de hand liggende respons. Updaten heeft te maken met het vernieuwen en bijwerken van informatie in het werkgeheugen, door niet langer bruikbare informatie weg te halen en relevante nieuwe informatie toe te voegen. Switchen is de vaardigheid om flexibel te kunnen wisselen tussen strategieën en taken. Een belangrijke bevinding uit eerder onderzoek is dat de executieve functie updaten een positief effect heeft op zowel rekenen (Friso- Van den Bos, Van der Ven, Kroesbergen, & Van Luit, 2013; Van der Ven, Kroesbergen, Boom, & Leseman, 2012) als creativiteit (Benedek, Jauk, Sommer, Arendasy, & Neubauer, 2014). Ook is duidelijk dat inhibitie een nuttige vaardigheid is tijdens rekenen (Friso-Van den Bos, et al., 2013). Hoe switchen en inhibitie samenhangen met creativiteit is echter nog niet duidelijk. Hoewel er aanwijzingen zijn dat de flexibele toepassing van kennis en omgevingsinvloeden en het onderdrukken van onoriginele, ineffectieve strategieën positief zou kunnen zijn voor creativiteit (Benedek. Franz, Heene, & Neubauer, 2012; Burch, Hemsley, Pavelis, & Corr, 2006; Pan & Yu, 2018), zijn er ook bronnen die aangeven dat er juist een negatieve relatie bestaat tussen creativiteit en inhibitie (Carson, Peterson, & Higgins, 2003; Gonzalez-Carpio, Serrano, & Nieto 2017).

In het verlengde van de discussie over de rol van inhibitie tijdens creatieve activiteiten ligt het debat over de rol van aandacht en afleiding bij creatief denken. Hoewel de rol van vroege filtering van stimuli en aandachtsprocessen in de hersenen bij creativiteit nog weinig wordt onderzocht, is er op gedragsniveau eerder een connectie aangetoond tussen afleidbaarheid, verminderde of verdeelde aandacht en creativiteit (Hoogman, Stolte, Baas, & Kroesbergen, 2020). Verminderde corticale activatie in frontale hersengebieden zou kunnen leiden tot verhoogde creativiteit omdat de frontale cortex andere hersenengebieden inhibeert (Martindale & Greenough, 1973; Martindale & Hines, 1975). Wanneer de frontale activiteit laag is, ontstaat er een situatie waarin minder cognitieve controle en selectieve aandacht uitgeoefend wordt, wat mogelijk leidt tot een creatievere en flexibelere manier van denken. Aanvullend bestaan er ook bepaalde onbewuste filteringsprocessen die ervoor zorgen dat er niet te veel prikkels verwerkt moeten worden en het bewustzijn bereiken. Omdat het maken van een groot aantal associaties belangrijk lijkt te zijn voor creativiteit en divergent denken zou het zo kunnen zijn dat een bredere aandachtfilter, die naast relevante stimuli ook irrelevante stimuli doorlaat, op dit vroege niveau gunstig is voor creativiteit (Chrysikou, 2019; Hommel, 2012). Hoe deze relatie tussen aandacht, inhibitie en creativiteit precies werkt, wordt uit eerder onderzoek nog niet duidelijk. Er zijn namelijk ook indicaties dat sterke cognitieve controle juist gunstig is voor creativiteit en het bedenken van originele oplossingen (Mayseless, Eran, & Shamay-Tsoory, 2015; Zabelina & Ganis, 2018). Om erachter te komen hoe deze relatie precies werkt is onderzoek nodig dat de rol van aandacht en executieve functies op verschillende niveaus meet om dit complexe proces in meer detail te kunnen bekijken.

Dit proefschrift

Het doel van dit proefschrift was om de cognitieve en neurale aspecten te identificeren die ten grondslag liggen aan (rekenkundige) creativiteit bij basisschoolkinderen. Ten eerste is de rol van de executieve functies, algemene rekenvaardigheden en creativiteit op rekenkundige creativiteit onderzocht. Naast executieve functies in het algemeen, is ook onderzocht of inhibitie een modererende rol heeft in de relatie tussen standaard rekenvaardigheden en creatief rekenen. Ten tweede werpt dit proefschrift een licht op de rol die vroege aandachts- en filteringprocessen in de hersenen spelen bij creatief denken en aandachtsproblemen.

Samenvatting van de empirische hoofdstukken

In *Hoofdstuk 2*, het eerste empirische hoofdstuk van dit proefschrift, stond de vraag centraal of inhibitie een modererende factor is tussen standaard rekenvaardigheden en creatief rekenen. We rapporteren onze bevindingen van ons onderzoek waarbij op een basisschool een aantal taken zijn afgenomen in een steekproef van kinderen in groep 5, 6 en 7 (N = 82). De deelnemende kinderen hebben een creatieve, divergente rekentaak gedaan waarbij meerdere antwoorden goed waren bij elke vraag. Zo werd bijvoorbeeld gevraagd hoe een vierkante taart op een eerlijke manier kon worden verdeeld onder vier kinderen en of hier meerdere antwoorden mogelijk waren. Deze rekentaak werd op drie verschillende aspecten gescoord. Vloeiendheid betreft het aantal goede antwoorden dat werd gegeven. Onder flexibiliteit werd verstaan het aantal verschillende antwoordcategorieën dat door het kind was gebruikt. Originaliteit was hoe vaak een antwoord was gegeven ten opzichte van een referentiegroep. Om inhibitie te meten deden de kinderen een taak, waarbij ze steeds een rij met vijf vissen zagen en zo snel en accuraat mogelijk moesten aangeven in welke richting de middelste vis van deze rij zwom. Wanneer alle vissen dezelfde kant op zwemmen is dit een relatief gemakkelijke opdracht en is maar een zeer beperkte mate van inhibitie vereist. Wanneer de omliggende vissen echter in de tegenovergestelde richting zwommen, moet deze informatie geïnhibeerd worden en zijn goede inhibitievaardigheden belangrijker. De resultaten lieten zien dat er een directe relatie was tussen standaard rekenvaardigheden en creatief rekenen. Inhibitie modereerde deze relatie voor flexibiliteit en originaliteit, waarbij verminderende inhibitie de relatie tussen rekenen en flexibiliteit/originaliteit versterkte. Bij kinderen met weinig rekenvaardigheden leek verminderde inhibitie rekenkundige creativiteit in de weg te staan door bijvoorbeeld het verhinderen van het adequaat onderdrukken van al gegeven antwoorden of onoriginele antwoorden (cf. Gilhooly, Fioratou, Anthony, & Wynn, 2007). Verminderde inhibitie leek creativiteit juist in de hand te werken bij kinderen met veel rekenvaardigheden, wellicht doordat zij hun rekenvaardigheden konden integreren met op het eerste gezicht irrelevante informatie, wat samen tot creatieve antwoorden leidde.

In *Hoofdstuk 3* zijn twee modellen over de link tussen executieve functies, creativiteit en rekenen met elkaar vergeleken op basis van onze steekproef met 278 kinderen tussen de 8 en 13 jaar oud. Dit onderzoek had een vergelijkbare opzet als het onderzoek uit *Hoofdstuk 2* en gebruikte dezelfde taken voor inhibitie, rekenvaardigheden en rekenkundige creativiteit. Omdat uit voorgaand onderzoek is gebleken dat updaten een positief effect heeft op creativiteit en rekenen (Benedek et al., 2014; Friso- Van den Bos et al., 2013; Van der Ven et al., 2012) was onze hypothese dat updaten tevens een rol speelt bij rekenkundige creativiteit. Daarnaast was onze verwachting dat alleen de executieve functie updaten een significante relatie zou vertonen met rekenkundige creativiteit wanneer alle drie de functies aan het model worden toegevoegd (Van der Ven et al., 2012). Ons eerste model testte of de executieve functies (switchen, updaten en inhibitie), rekenvaardigheid en creativiteit allemaal een directe relatie hadden op rekenkundige creativiteit. Ons tweede model testte dezelfde hypothesen met twee aanvullende paden: of updaten een mediërende factor was tussen creativiteit en rekenkundige creativiteit en ook tussen rekenvaardigheid en rekenkundige creativiteit. Uit onze resultaten bleek dat het tweede model beter de data kon verklaren dan het eerste model. Daarnaast vonden we ook dat, hoewel switchen en inhibitie wel een positieve correlatie vertoonden met rekenkundige creativiteit, deze relatie verdween wanneer updaten aan het model werd toegevoegd, vermoedelijk door gedeelde verklaarde variantie van de executieve functies. Hoewel dit onderzoek cross-sectioneel was en er daarom geen uitspraken gedaan kunnen worden over causaliteit, suggereren de gevonden verbanden dat updaten op een directe en indirecte manier een positieve invloed heeft op rekenkundige creativiteit. Vermoedelijk faciliteert updaten het bedenken van creative uitkomsten doordat updaten het mogelijk maakt om tussentijdse antwoorden en ideeën op te slaan in het werkgeheugen en de informatie in het werkgeheugen te vernieuwen. Toekomstig onderzoek is nodig om uit te wijzen of de geïmpliceerde causale verbanden ook daadwerkelijk gevonden worden en hoe de relatie tussen creativiteit, rekenen en executieve functies verandert tijdens de ontwikkeling van basisschoolkinderen.

Hoofdstuk 4 en Hoofdstuk 5 beschrijven onze bevindingen uit het elektro-encefalografie (EEG)-onderzoek dat is uitgevoerd in het UMC Utrecht naar de connectie tussen sensorisch en sensomotorisch filteren, selectieve aandacht, cognitieve controle, aandachtsproblemen en creativiteit. Dit verband hebben we onderzocht door middel van het meten van de elektrische activiteit in de hersenen door middel van het plaatsen van elektroden op het hoofd op een non-invasieve manier.

In *Hoofdstuk 4* is onderzocht of een verminderde mate van sensorisch en sensomotorisch filteren van informatie uit de omgeving gerelateerd is aan meer creativiteit en/of meer aandachtsproblemen bij kinderen. De taak om sensorisch filteren te meten bestond uit een reeks van paren van auditieve stimuli. Hiermee werd P50 suppressie gemeten, een maat die de invloed van inhibitieprocessen van eerder gepresenteerde stimuli weergeeft (Madsen et al., 2015; Oranje, Geyer, Bocker, Kenemans, & Verbaten., 2006). Met andere woorden, een verminderde response is zichtbaar bij gezonde proefpersonen wanneer er eerst een zachte auditieve stimulus wordt gepresenteerd gevolgd door een luide stimulus. Sensomotorisch filteren werd gemeten met prepulse inhibitie van de schrikrespons door middel van een elektromyografie (EMG) van de orbicularis oculispier (Gebhardt, Schulz-Juergensen, & Eggert, 2012; Madsen, Bilenberg, Cantio, & Oranje, 2014). De resultaten van dit onderzoek laten zien dat kinderen met een hogere P50 amplitude op de teststimuli (de tweede auditieve toon) een significant hogere score voor vloeiendheid en flexibiliteit hebben (n = 65). We vonden geen verschillen op basis van de andere creativiteitsmaten, aandachtsproblemen of wanneer de groep was gesplitst op basis van sensomotorisch filteren, behalve dat de creativiteitsscores hoger waren voor de creatieve tekentaak in de lagere sensomotorische groep bij één van de vier soorten trials (n = 37). Dit laatste resultaat wordt mogelijk verklaard door een zeer kleine groepsgrote in één van de groepen. De overige resultaten geven aan dat informatie uit de omgeving die misschien op het eerste gezicht irrelevant lijkt, maar toch het werkgeheugen bereikt door verminderde filtering, wellicht nuttig kan zijn voor creatieve opdrachten waarbij om meerdere oplossingen gevraagd wordt. Aanvullend suggereren deze resultaten dat aandachtsproblemen, zoals ook gevonden bij de diagnose ADHD, niet het resultaat zijn van een algemeen filteringsprobleem op dit vroege onbewuste aandachtniveau maar wellicht meer te maken hebben met bewuste aandachtsprocessen zoals bijvoorbeeld cognitieve controle (Conzelmann et al., 2010). Verder onderzoek is nodig om dit te bestuderen door bijvoorbeeld actieve en passieve luisterparadigma's te vergelijken en door naast divergente creativiteitstaken ook het effect van sensorisch filteren op convergente taken en creatieve prestaties te analyseren.

Ten slotte zijn we in *Hoofdstuk 5* dieper ingegaan op de mogelijke associatie tussen cognitieve controle, creativiteit en aandachtsproblemen op basis van data die we hebben verkregen uit een selectieve aandachtstaak (N = 62). Deze taak bestond uit twee delen. In het eerste deel moesten de proefpersonen op een knop drukken wanneer zij een afwijkende toon in hun linkeroor hoorden in een reeks van standaard tonen. In het tweede deel moesten zij op de knop drukken wanneer zij een afwijkende toon in hun rechteroor hoorden. Cognitieve controle werd gemeten door middel van de amplitude die in de hersenen tot stand kwam naar aanleiding van het moeten switchen van de aandacht en het evalueren van de stimulus bij de afwijkende tonen (P300 amplitude; Polich & Criado, 2006) en door middel van de amplitude die tot stand komt naar aanleiding van conflict- en mismatch detectie (N200 amplitude; Nieuwenhuis, Yeung, Van den Wildenberg, & Ridderinkhof, 2003). Daarnaast hebben we ook gekeken naar de onbewuste response van de hersenen die tot stand komt op basis van het detecteren van een afwijkende stimulus, de mismatch negativiteit (MMN; Näätänen, 1995). Onze resultaten wijzen uit dat meer creativiteit gerelateerd is aan verlaagde cognitieve controle, zoals te zien was aan een significant grotere, positievere N200 amplitude en een significant kleinere P300 amplitude op de relevante afwijkende trials. Deze verminderde cognitieve controle had echter geen invloed op de taakprestatie van de kinderen. Een mogelijke verklaring voor deze resultaten kan zijn dat verminderde cognitieve controle leidt tot het maken van meer associaties tussen stimuli en bestaande kennis, doordat associatieve gebieden in de hersenen meer energie krijgen. Deze kunnen kinderen tijdens creatieve taken inzetten om originele antwoorden te bedenken. Daarnaast bleek dat verminderde cognitieve controle op de standaardtrials, zoals gemeten door meer positieve N200 amplitudes, was gecorreleerd met significant meer aandachtsproblemen zoals gemeten met een oudervragenlijst over het gedrag van de deelnemende kinderen. Verder leverden de resultaten extra bewijs voor de connectie tussen verminderde cognitieve controle en ineffectieve executieve controle omdat bleek dat kinderen met aandachtsproblemen ook daadwerkelijk minder goed presteerden op de selectieve aandachttaak.

Conclusie en Discussie

In *Hoofdstuk 6* wordt een overzicht gegeven van de onderzoeksresultaten uit dit proefschrift waarin deze bevindingen worden bediscussieerd. De resultaten van dit proefschrift geven een overzicht van zowel gedragsmatige als (neuro)cognitieve aspecten in relatie tot creativiteit en creatief rekenen. Daarom hebben we op basis van onze resultaten en aan de hand van het socio-cultureel en perceptie-actie perspectief van creativiteit (Corazza & Glăveanu, 2020) een nieuw model van creatieve cognitie voorgesteld in dit hoofdstuk waarin de interactie tussen de omgeving, de lichamelijke en neurologische aspecten van perceptie en de kennis en vaardigheden van het individu tezamen tot creatief denken leiden.

De huidige resultaten dragen aanzienlijk bij aan educatieve doeleinden, aangezien het hoofddoel van onderwijs is om kinderen voor te bereiden op het bedenken van oplossingen voor complexe problemen die ze in de echte wereld zullen tegenkomen, waarvoor creativiteit vereist is (Sternberg, Lubart, Kaufman, & Pretz, 2005). Omdat creativiteit slechts een kleine rol speelt in de huidige theorieën over ontwikkeling en educatie, wordt de nadruk vooral gelegd op het belang van convergent denken en gefocuste aandacht. Zoals de titel van dit proefschrift aangeeft kan gesteld worden dat meer aandacht en oplettendheid voor de concepten creativiteit, divergent denken en gedistribueerde aandacht ook vele voordelen met zich mee brengt.

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About the author

Curriculum Vitae

Marije Stolte was born on December 13th 1991 in Goes, The Netherlands. After graduating high school in 2010 (Ostrea Lyceum Goes), Marije moved to Leiden where she received a Bachelor's degree in Psychology in 2013 and obtained her Research Master's degree in Cognitive Neuroscience (cum laude) in 2016 from Leiden University. During her master, she completed an internship at the Cognitive Psychology Unit where she later went on to work as a student assistant. She wrote her thesis and collected behavioral and functional MRI data at the Brain and Development Lab at Leiden University. In 2016, Marije started her doctoral research at Utrecht University to investigate the connection between executive functions, creativity, and mathematics in primary school children under supervision of Prof. dr. Hans van Luit and Prof. dr. Evelyn Kroesbergen. In 2017, dr. Bob Oranje joined as a supervisor and as principal investigator of the EEG study that focused on the relation between creativity, attentional processes and sensory gating at UMC Utrecht. Marije presented her research findings on various conferences across the globe, for which she received a travel grant by the National Science Foundation, and published in peer-reviewed journals.

In addition to research, Marije was involved in various other activities at Utrecht University and Radboud University. Marije supervised bachelor and master students during their thesis, taught workgroups, gave lectures, and was involved in the coordination of courses. In addition, she co-organized three international creativity conferences and was a member of the Faculty Election Committee.

List of publications

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